PRIMER ZAŠTITE DUBOKE TEMELJNE JAME I SUSEDNIH OBJEKATA U SLOŽENIM URBANIM I GEOTEHNIČKIM USLOVIMA

EXAMPLE OF PROTECTION OF DEEP FOUNDATION PIT IN COMPLEX URBAN AND GEOTECHNICAL CONDITIONS

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1 UVOD

Budući stambeno-poslovni objekat „Pupinova palata“ nalazi se na uglu ulice Narodnih heroja i Bulevara Mihajla Pupina, u strogom centru Novog Sada. Objekat je moderno arhitektonsko rešenje, u kojem su objedinjeni poslovni i uslužni sadržaji koje predviđ a stroga urbana sredina grada, klasične stambene jedinice, elitni stambeni deo na najvišem spratu, sa zelenim krovom (penthaus), trospratna podzemna garaža sa 400 parking mesta za vlasnike objekta, s direktnom lift-vezom do svakog sprata i javna podzemna garaža za posetioce.

Ukupna površina objekta jeste oko 43.000 m². Objekat ima raznu spratnost – koja iznosi P+4, P+5, P+7, P+8 do P+12 na delu najviše kule – s tim što u nivou prizemlja ima i dva atrijuma za dodatnu komunikaciju, kao i vezu s kružnim požarnim putem.

S obzirom na to što je lokacija u strogom centru, okružena je starim postojećim objektima čija se spratnost kreće od P+1 do P+3, a konstruktivni sistem je zidani, s pruskom tavanicom, bez serklaža, dok samo manji deo objekata ima podrum. Građevinska linija novog objekta – u skladu s lokacijskim uslovima – nalazi se neposredno na liniji gabarita postojećih objekata, što omogućava maksimalno iskorišćenje postojeće površine građevinske parcele.

1 INTRODUCTION

The future residential and commercial building "Pupin's Palace" is located on the corner of Narodnih heroja street and boulevard Mihajlo Pupin in the very centre of Novi Sad. The building is a modern architectural solution that combines business and service facilities that are planned by a strict urban city centre, classic residential units, in elite residential area on the highest floor with a green roof (pent house), a three-story underground garage with 400 parking spaces for the owners of the facility with direct elevator-link to each floor and a public underground garage for visitors.

The total area of the building is about 43,000m². The building has different floors, which are 4, 5, 7, 8 to 12 on the part of the highest tower, and two atriums at the ground level for additional communication, and a connection with a circular fire route.

Since the location is in the centre of the city, it is surrounded by old existing buildings, the floor of which is from 1 to 3, and the constructive system is masonry, with a Prussian ceiling, without stiffness rib, and only a small part of the building has a basement. The construction line of the new facility is in line with the location conditions directly on the line of the existing buildings, which allows the max utilization of the existing surface.

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Slika 1. Izgled budućeg objekta „Pupinova palata” u Novom Sadu
Figure 1. The appearance of the future "Pupin's Palace" building in Novi Sad

Pre početka radova, svi susedni objekti detaljno su pregledani i snimljeni, u prisustvu stručnog sudskog veštaka, utvrđena su sva oštećenja u vidu prslina i pukotina, te je urađen poseban elaborat postojećeg stanja objekata.

Na predmetnoj lokaciji, pre početka radova, urađena su i detaljna geomehnička ispitivanja, koja su obuhvatila sondažne bušotine i oglede statičke penetracije (CPTu). Na osnovu terensko-laboratorijskih ispitivanja, utvrđeno je da profil terena predstavlja aluvion reke Dunav, koji izgrađuje čist pesak s tankim horizontalnim proslojcima zaglinjenog peska, u čijoj se podini pojavljuje peskovit sitnozrnasti do srednjezrnasti šljunak. Na dubini od 22–23 m pojavljuje se laporovita glina.

Teren je na lokaciji u blagom padu ka jugoistoku od 78.8 do 77.6 m nadmorske visine. U hidrogeološkom pogledu, sloj peska u direktnoj je hidrauličkoj vezi s Dunavom, tako da se dubina podzemne vode – u zavisnosti od vodostaja reke – kreće od minimalnih cca 1.0 m do maksimalnih cca 6.0 m. U toku istražnih radova (jun 2015), dubina podzemne vode bila je između 2.2–3.4 m od postojeće površine terena, odnosno na koti cca 75.3–75.5 metara nadmorske visine.

Gabaritna površina budućeg objekta jeste 4.100 m², a gabaritni obim – oko 301 m¹. Kao što je na Slici 2. evidentno, gabarit objekta okružen je postojećim objektima koji su neposredno na građevinskoj liniji, kao i vrlo frekventnim saobraćajnicama. U takvom, vrlo nepovoljnom okruženju, koje se ogleda u starim susednim objektima, relativno visokom nivou podzemne vode, visokoj vodopropusnosti tla i minimalnom rastojanju krajnjih naspramnih strana zidova podzemne etaže od cca 36 m, trebalo je izvesti temeljnu jamu dubine 9 metara.

All adjacent objects were carefully inspected and recorded in the presence of a professional forensic expert, before the beginning of the work, by identifying all damages in the form of cracks, and a special study of the existing condition of the objects was made.

At the site, detailed geomechanical tests, including borings and static penetration (CPTu), were made before the beginning of the work. On the basis of field-laboratory tests, it was determined that the terrain profile represents the alluvium of the Danube river, which build clean sand with thin horizontal clayey-sand, at which bottom the sandy fine to medium-sized pebbles appear. At a depth of about 22–23 m, a clayey marl appears.

The terrain is a gentle slope towards southeast from 78.8–77.6m. In hydrogeological terms, the sand layer is in direct hydraulic connection with the Danube, so the depth of ground-water depending on the water level of the river, ranges from a min. 1.0m to a max. of 6.0m. During the geotechnical works (June 2015), the depth of the groundwater was between 2.2–3.4m from the existing surface of the terrain, or at sea level of approx. 75.3–75.5 m.

The basis area of the future object is 4,100m², and the circuit is about 301m¹. As shown in Figure 2, the facility's dimensions are surrounded by existing facilities that are directly on the construction line and busy street with heavy traffic. In such a very unfavourable environment, which is reflected in the old neighbouring buildings, a relatively high level of groundwater, high soil permeability and a min. distance of the final opposite sides of the walls of the underground floor of approx. 36m, a pit of 9m depth was to be performed.

Slika 2. Situacioni prikaz položaja objekta „Pupinova palata” u Novom Sadu
Figure 2. Display of the position of the "Pupin's Palace" building in Novi Sad

Analizirajući moguće varijante rešenja, u svim slučajevima zaključak jeste da je najbolje AB dijafragme spustiti do laporovite gline i time izbeći jak priliv podzemne vode i formiranje dubokog depresionog levka oko temeljne jame. Dijafragma je do dubine 15 m konstruktivna, a ispod toga je nearmirana i služi kao svojevrsna protivfiltraciona zavesa. Time se povećava površina dijafragmi za cca 2.100 m², što znači veću količinu i cenu iskopa i kontraktorskog betona, u iznosu od cca 190.000 evra. Međutim, realna dobit višestruko nadmašuje ovaj gubitak.

Prva dobit od izrade dublje dijafragme jeste to što se izbegava izrada 8-9 bunara bušenih do sloja laporovite gline, s pojedinačnim kapacitetom oko 20–25 l/s, koji zahtevaju složen potisni vod, dvadesetčetvoročasovni nadzor, stalnu pripravnost dizel agregata velike snage, prihvati i do 200 l/s podzemne vode iz bunara u sistem javne kanalizacije koja nema mogućnost prijema te količine vode u slučaju velike kiše, kao i troškove naknade JKP-a oko 40 evra dnevno po bunaru. Za procenjeno trajanje radova od minimum osam meseci, dok se s težinom konstrukcije ne savlada uzgon podzemne vode, samo troškovi naknade za JKP jesu oko 90.000 evra. Ako se na to još dodaju troškovi izrade osam-devet bunara s potisnim cevovodima, stalni nadzor i najam dizel agregata, iznos raste do oko 140.000 evra.

Nadalje, izradom dublje dijafragme, izbegava se formiranje širokog depresionog levka, koje bi nastalo intenzivnim dugotrajnim crpljenjem podzemne vode bunarima unutar temeljne jame. Takav depresioni levak, pri postojećem nivou podzemne vode, imao bi dubinu

Analyzing the possible variants of the solution, in all cases, it was concluded that the best diaphragm wall are to be lowered to the marl, thereby avoiding a strong inflow of groundwater and forming a deep depression funnel around the foundation pit. The diaphragm wall is constructive to the depth of 15m, and below it non-reinforced and serves as a kind of anti-filtration curtain. This increases the surface of the diaphragm wall by approx. 2,100m², which means a higher quantity and price of excavation and concrete, in the amount of approx. 190,000€. However, real profits outweigh this loss altogether.

The first gain from making the deeper diaphragm wall is that the generation of 8-9 wells drilled to a layer of marble clay with an individual capacity of about 20-25 l/s, requiring a complex pressure line, 24h control, constant standby power of high-power diesel units, 200 l/s of groundwater from the wells into a public sewage system that does not have the possibility of receiving this amount of water in case of heavy rainfall, and the cost of compensation for "JKP vodovod i kanalizacija" about 40€/day/well. For an estimated duration of works of at least 8 months, while the weight of the construction is not overgrown the uplift pressure, only the cost of the compensation is about 90,000€. If there are additional costs for the construction of 8-9 wells with pressure pipelines, constant monitoring and leasing of diesel engines, the amount increases to around 140,000€.

Secondly, by creating a deeper diaphragm wall, the formation of a wide depression funnel is avoided by intensive long-term drainage of groundwater with wells

oko 6 m, što bi prema proračunima izazvalo sleganja (zbog porasta efektivnih napona u tlu do 60 kPa) koja iznose cca 4-5 cm nesposredno oko dijafragme, a postepeno bi se smanjivala udaljavajući od nje. Svi susedni objekti bili bi zahvaćeni depresionom zonom širine 15-30 m, u kojoj bi trpeli neravnomerna sleganja koja bi – zbog njihovog konstruktivnog sklopa – izazvala vidna oštećenja u vidu cm-pukotina u zidovima, što je neprihvatljivo.

Izrada bunara unutar temeljne jame ima i dodatan zahtev za posebnu obradu otvora u temeljnoj ploči debljine 80 cm, za prolaz bunarskih cevi, koje se po prestanku potrebe za crpljenjem vode moraju posebnim postupkom hermetički zatvoriti. To je dodatni neizbežni deo koji se mora raditi vrlo pažljivo, uz postepeno isključivanje/uključivanje rada pojedinih bunara, sa stalnom regulacijom proticaja, kako bi se sprečilo nadiranje podzemne vode.

Nakon što je odlučeno da se urade duboke dijafragme, analizirana su konstruktivna rešenja razupiranja. Poseban problem predstavljala je velika širina temeljne jame, koja je na najužem delu široka oko 36 metara. Ponuđene su tri varijante rešenja. Prvo rešenje bila je tzv. Top-Down metoda. To je sistem koji je odavno poznat, a koristi se u urbanim sredinama, na malom prostoru, kada je potrebna brza gradnja. Sistem podrazumeva istovremenu gradnju i podzemnih i nadzemnih etaža. Investitor – koji je ujedno bio i izvođač radova – procenio je da je ova metoda vrlo složena i skupa, jer dodatno zahteva izradu više stotina dubokih šipova velikog prečnika – kao oslonaca stubova objekta, podzemni iskop i transport, angažovanje obimne radne snage na malom prostoru i vrlo složenu organizaciju gradilišta.

Kao sledeće rešenje, detaljno je analizirana varijanta otkopa temeljne jame s paralelnom izradom prethodno napregnutih sidara koje bi obezbeđivale stabilnost dijafragme pri velikim bočnim pritiscima tla i podzemne vode. Imajući u vidu aluvijalne sedimente kao sredinu u kojoj bi se formirala sidrišna zona, računski kapacitet sidara bio je relativno mali, oko 250-300 kN, što je zahtevalo vrlo velik broj sidara (oko 600 komada), postavljenih u dva nivoa; cena bi bila oko 500.000 evra. Mada je investitor bio spreman na tu investiciju, budući da se dobija široka, sigurna i otvorena temeljna jama bez razupirača i privremenih bermi, od ove varijante odustalo se zbog zakonskih prepreka. Naime, prema srpskom zakonu, izradom ankera ulazi se u privatno vlasništvo suseda, od kojih investitor mora dobiti overenu pismenu saglasnost, a što je – s obzirom na već postojeće odnose sa susedima – procenjeno kao nemoguće.

Na kraju, investitor se odlučio na varijantu faznog iskopa temeljne jame uz fazno razupiranje dijafragme horizontalnim čeličnim razupiračima, pri čemu se kao obostrani oslonci razupirača koriste dijafragme, a kao dodatni jednostrani oslonci – već izvedeni podzemni delovi objekta. Generalno, usvojeno je pet (V) faza iskopa s razupiranjem, koji su u periodu od 6-7 meseci omogućili da se kompletna temeljna ploča na poslednjoj fazi, pri čemu je na prvoj fazi objekat završen približno do nivoa petog sprata.

Za potrebe crpljenja zarobljene podzemne vode unutar gabarita dijafragme, urađena su dva bunara kapaciteta od oko 15 l/s. Ovi bunari su napravljeni i

inside the foundation pit. Such a depressed funnel would have a depth of about 6m at the existing groundwater level, which would have led to settlements according to the calculations (due to an increase in the effective voltage in the soil to 60kPa), which would be about 4-5cm near to the diaphragm wall and gradually decrease away from it. All adjacent objects would be affected by a depression zone of 15-30m wide, in which they would suffer uneven settlements that would cause visible damages in the form of cm-cracks in the walls due to their poor building structure, which is unacceptable.

The construction of the well inside the foundation pit has additional requirements for the special treatment of openings in the 80cm thick foundation slab for the passage of well tubes which, after the need for water extraction, must be sealed by a special procedure. This is an additional inevitable part, which must be done very carefully, with the gradual shutdown-activation of the work of individual wells, with constant flow control in order to prevent the overflow of groundwater.

After deciding to do deep diaphragm wall, constructive solutions of bracing were analyzed. A special problem was the large width of the foundation pit, which is at the narrowest part about 36m. Three variants of the solution are offered. The first solution was the so-called. method "Top-Down". It is a system that has been known for a long time, and is used in urban part, in a small area, when rapid construction is required. The system implies the simultaneous construction of both underground and above ground floors. The investor, who was also the contractor, estimated that this method is very complex and costly, as it additionally requires the production of hundreds of deep piles of large diameter as supports of the columns, underground excavation and transport, engaging large workforce in a small space and very complex organization of construction sites.

As the next solution, in detailed are analyzed the variant of the excavation of the foundation pit with parallel production of pre-stressed anchors, which would ensure the stability of the diaphragm wall at large lateral soil and water pressures. Beyond a weak alluvial sediments as the anchor zone, the calculated capacity of the anchors was relatively small, about 250-300kN, which required a very large number of it, about 600, which would be placed in two levels, and the price it was around 500,000€. Although the investor was ready for this investment, which will give a wide, safe and open pit without braces and berms, this variant was abandoned due to legal obstacles. Namely, according to the Serbian law, the anchor enters the private ownership of the neighbours, of which the investor must obtain a certified written consent, which, given the mutual relations is estimated as impossible.

In the end, the investor decided on a variant of the phase excavation of the foundation pit with horizontal steel braces, relying on the diaphragm wall, and on the already constructed underground parts of the building. In general, a five (5) phase of excavation was adopted, which in the period of about 6-7 months enabled the completion of the foundation slab at the last stage, with the first stage being completed approximately to the level of 5 floors.

For the needs of the pumping of captured groundwater inside the circuit of diaphragm wall, two wells with capacity of about 15 l/s were made. These

aktivirani neposredno po završetku dijafragme. Prema proračunu, nivo podzemne vode unutar temeljne jame trebalo je biti snižen na 50 cm ispod dna budućeg iskopa za jedanaest dana. Međutim, merenjem nivoa na dva kontrolna piezometra, utvrđeno je da sniženje ne napreduje po planiranoj dinamici. Analizom rezultata i dopunskim hidrauličkim proračunom, zaključeno je da postoji konstantan doticaj podzemne vode u količini oko 7 l/s, što usporava snižavanje nivoa u temeljnoj jami. Takođe, zaključeno je da je razlog za to bio u procurivanju na spojevima kampade dijafragme, što je bilo očekivano s obzirom na ukupan broj spojeva od oko 120, s pojedinačnom dužinom ispod podzemne vode oko 16 m, što je ukupno oko 2 km spojeva. Nakon sniženja podzemne vode na planirani nivo za oko 22 dana, nastavljeno je crpljenje u iznosu od 4-5 l/s do završetka kompletne temeljne ploče.

2 GEOTEHNIČKI USLOVI NA LOKACIJI

Šire područje oko lokacije pripada krajnjem južnom delu velike bačke ravnice koja se prostire od državne granice na severu do Fruške gore na jugu. Morfologija terena je tipično ravničarska, blago zatalasana, aluvijalno fluvijalnog porekla. Nadmorska visina lokacije, u blagom padu prema jugoistoku, kreće se između 78.8 do 77.6 m nadmorske visine. Predmetna lokacija jeste neuređen parking prostor (Slika 3), u strogom centru Novog Sada, koji svojim izgledom godinama narušava gradsko jezgro.

wells were created and activated immediately after the end of the diaphragm wall. According to the budget, the groundwater level within the foundation pit was to be reduced to 50cm below the bottom of the future pit in 11days. However, by measuring the level on two control piezometers it was established that the reduction is unlikely to progress according to the planned dynamics. By analyzing the results and the additional hydraulic calculation, it was concluded that there is a constant inflow of groundwater in the amount of about 7 l/s, which slows down the level reduction. It was concluded that the reason was in the flow leakage on the joints of the diaphragm wall, which was expected due to the total number of joints of about 120, with an individual joint length below the ground water of about 16m, which is a total of about 2km of joints. After lowering the groundwater to the planned level in about 22 days, it continued with pumping in the amount of 4-5 l/s to the end of the completion of the slab.

2 GEOTECHNICAL CONDITIONS AT THE LOCATION

The wider area around the site belongs to the far southern part of the big bačka plain which extends from the state border in the north to Fruška Gora in the south. The morphology of the terrain is typically a flat, slightly stratified, alluvial fluvial origin. The altitude of the site, slightly down to the southeast, ranges from 78.8-77.6m. The location is an unregulated parking space (Fig 3), in the strict centre of Novi Sad, disturbing the city core for years.

Slika 3. Izgled parcele za objekat „Pupinova palata” u Novom Sadu
Figure 3. View of the parcel for the "Pupin's Palace" building in Novi Sad

Primarna morfologija izmenjena je antropogenim uticajem prilikom urbanizacije, što potvrđuje sloj antropogenog nasipa promenljive debljine, utvrđenog istražnim bušenjem, dok dublje slojeve izgrađuju kvartarni sedimenti (OGK Srbije: List 34-100 Novi Sad), holocene starosti preko sedimenata neogena (pliocen).

Kvartarni sedimenti javljaju se u faciji starača (am), kao i u faciji korita i povodnja (alp), koje izgrađuju najmlađi deo aluvijalne ravni Dunava, u čijem sastavu preovlađuju organogeno-barski pesak, razni alevriti i alevritske gline. U faciji korita preovlađuju srednjeznasti do krupnozrni šljunak i sivi srednjezrni pesak, dok faciju povodnja predstavljaju žuti, liskunski, alevritski pesak i

Primary morphology has been changed by influence in the urbanization process, which is confirmed by the layer of building dump of variable thickness, determined by investigative drilling, while deeper layers are constructed by quaternary sediments (OGK Srbije: List 34-100 Novi Sad), Holocene ages through sedimentary Neogene's (Pliocene).

Quaternary sediments occur in the facies of the aging (am), as well as in the facies of the wrecks (alp), which build the youngest part of the alluvial plane of the Danube, which consists of organogenic-sand, various alevrites and alevritic clays. The facies of bed prevail medium to large-scale gravel and gray medium-sized

peskoviti alevriti.

Neogeni sedimenti pružaju se u podini šljunka facije korita. Javljaju se u vidu laporovitih glina pliocene starosti. Laporovite gline su žute do tamnosmeđe boje, prašinstog sastava, s tankim proslojcima i sočivima peska, vrlo niske vodopropusnosti.

Na predmetnoj lokaciji, osim sondažnih bušotina, urađeno je i više penetracionih ispitivanja (CPTu), tačnije ukupno pet, a tipičan penetracioni profil prikazan je na Slici 4.

sand, while the facies of the basin is represented by yellow, marshy, alevritic sand and sandy alevrites. Neogene sediments are provided in the underground gravel facies of bed. They appear in the form of clayey marl of Pliocene age. Clayey marl are yellow to dark brown colour, very low permeable, silty composition, with thin sediments and sand lenses. At the site, besides drill holes, a number of penetration tests (CPT) were performed, a total 5 pieces, and a typical penetration profile is shown in Fig. 4.

Slika 4. Tipičan penetracioni profil (CPTu4) na predmetnoj lokaciji
Figure 4. A typical penetration profile (CPTu4) at the site

Koristeći rezultate statičke penetracije (CPTu), mogu se korelirati neki parametri tla, kao što su vodopropusnost, broj udaraca N_{60} iz standardnog penetracionog oglada (SPT), Young-ov modul elastičnosti za nivo mobilizovane deformacije od 10^{-3} (Robertson, 2009), relativna zbijenost, ugao smičuće čvrstoće (Kulhawy & Mayne, 1990) i drugo (Slika 5).

Rezultati laboratorijskih ispitivanja i korelacije, na osnovu CPTu, korišćeni su u okviru projekta zaštite temeljne jame, za definisanje naponsko-deformacijske karakteristike tla za numeričku simulaciju, u softverskom paketu „GeoStudio”. Na osnovu istražnih bušotina i laboratorijskih ispitivanja, na datoj lokaciji mogu se izdvojiti sledeći litološki članovi:

1) Nasip (n), izgrađen pretežno od prašinsto-peskovitog materijala (ML,SF), pomešanog s čvrstim građevinskim otpadom. Zapreminska težina sloja jeste $\gamma \approx 19.5 \text{ kN/m}^3$, kohezija – $c' \approx 5.0 \text{ kPa}$, a ugao smičuće

Using the results of static penetration (CPTu), some soil parameters can be correlated, for example, permeability, number of impacts N_{60} from the standard penetration test (SPT), Young's modulus of elasticity at the 10^{-3} level of mobilized deformation (Robertson, 2009), relative compactness, angle of shear strength (Kulhawy & Mayne, 1990) and others (Fig. 5.)

The results of laboratory tests and correlations based on CPT's were used within the framework of the project for the protection of the foundation pit, for defining the stress-deformation characteristics of the soil, for numerical simulation in the software GeoStudio. Based on borings and laboratory tests, the following lithological members are identified:

1) Building dump (n), built mainly of dust-sandy material (ML, SF), which is mixed with solid construction waste. The bulk density of the layer is $\gamma \approx 19.5 \text{ kN/m}^3$, the cohesion is $c' \approx 5.0 \text{ kPa}$, the angle of shear strength

čvrstoće – $\phi' \approx 25^\circ$. Podina sloja je između 2–3 m od površine terena.

$\phi' \approx 25^\circ$. The floor of the layer is between 2-3m from the ground surface.

Slika 5. Tipičan rezultat korelacije nekih parametara tla na osnovu CPTu
Figure 5. A typical result of the correlation of some soil parameters based on CPT

2) Prašina (ML–CL) peskovita, malo zaglinjena, niskoplastična, meke konzistencije, tamnosive boje. Zapreminska težina sloja jeste $\gamma \approx 19.5 \text{ kN/m}^3$, kohezija – $c' \approx 2.0 \text{ kPa}$, a ugao smičuće čvrstoće – $\phi' \approx 23^\circ$. Podina sloja je na dubini oko 4.5–5 m od površine terena.

2) Silt (ML–CL) sandy, slightly clayey, low-plastic, soft consistency, dark gray. The bulk density of the layer is $\gamma \approx 19.5 \text{ kN/m}^3$, the cohesion is $c' \approx 2.0 \text{ kPa}$, the angle of shear strength $\phi' \approx 23^\circ$. The bottom of the layer is at ≈ 4.5 –5 m from the ground surface.

3) Pesak (SF–SC) sitnozrnast do srednjezrnast, sive do sivožute boje, u povlatnom delu prašinstiji, s povećanjem dubine – čistiji i bolje zbijen, u intervalima s primesama oksida gvožđa. U sloju su uočljiva sočiva šljunka, peščara i glinovite prašine meke konzistencije. Zapreminska težina sloja jeste $\gamma \approx 20.0 \text{ kN/m}^3$, kohezija – $c' \approx 1.0 \text{ kPa}$, a ugao smičuće čvrstoće – $\phi' \approx 32^\circ$. Podina sloja je na dubini između 15–19 m od površine terena.

3) Sand (SF–SC) fine to medium-sized, gray to gray-yellow, in the floor part more silty, and deeply cleaner and more dense, at intervals with admixtures of iron oxide. In the layer there are gravel, sandstone and clayey silt of soft consistency. The bulk density of the layer is $\gamma \approx 20.0 \text{ kN/m}^3$, the cohesion is $c' \approx 1.0 \text{ kPa}$, the angle of shear strength is $\phi' \approx 32^\circ$. The bottom of the layer is at a depth of 15-19 m from the surface of the ground.

4) Šljunak (GF, GW) peskovit, srednjezrnast do sitnozrnast, sive do sivoplave boje, u podinskom delu više peskovit, s proslojcima peskovite prašine crne boje i ostacima treseta. Zapreminska težina sloja jeste $\gamma \approx 21.0 \text{ kN/m}^3$, kohezija – $c' \approx 0 \text{ kPa}$, a ugao smičuće čvrstoće – $\phi' \approx 33^\circ$. Debljina sloja je između 1.7–3 m.

4) Gravel (GF, GW) sandy, medium to fine grains, gray to gray-blue, at the bottom more sandy, with sediments of black sandy silt and peat remains. The bulk density of the layer is $\gamma \approx 21.0 \text{ kN/m}^3$, the cohesion is $c' \approx 0$, the angle of shear strength $\phi' \approx 33^\circ$. The thickness of the layer is between 1.7-3m.

5) Prašina (ML–CL) peskovita, malo zaglinjena, niskoplastična, meke do srednjeplastične konzistencije, tamnosive boje, s primesama oksida gvožđa. Zapreminska težina sloja jeste $\gamma \approx 20.5 \text{ kN/m}^3$, kohezija – $c' \approx 7.0 \text{ kPa}$, a ugao smičuće čvrstoće – $\phi' \approx 28^\circ$. Sloj je utvrđen na dubini između 21.7–23 m od površine terena.

5) Silt (ML–CL) sandy, low clayey, low plastic, soft to medium-plastic consistency, dark gray, with admixtures of iron oxide. The bulk density of the layer is $\gamma \approx 20.5 \text{ kN/m}^3$, the cohesion is $c' \approx 7.0 \text{ kPa}$, the angle of shear strength $\phi' \approx 28^\circ$. The layer is determined at a depth between 21.7-23m from the surface of the terrain.

6) Glina (CI-CH) srednjeplastična do visokoplastična, tvrdoplastične konzistencije, žute do tamnosmeđe boje, s primesom oksida mangana i gvožđa i CaCO_3 u vidu praha i kongrecija cm-dimenzija. Zapreminska težina sloja jeste $\gamma \approx 20.5 \text{ kN/m}^3$, kohezija – $c' \approx 75.0 \text{ kPa}$, a ugao smičuće čvrstoće – $\phi' \approx 18^\circ$. Sloj se prostire do dna istražnog bušenja, do 35 m od površine terena.

Parametri deformabilnosti slojeva za numeričku simulaciju usvojeni su na osnovu rezultata terensko-laboratorijskih ispitivanja. Imajući u vidu nelinearnu vezu između parametra deformabilnosti i efektivnog napona, korišćena je sledeća jednačina (Duncan, 1980):

$$E = K p_a \left(\frac{k_0 \sigma'_v}{p_a} \right)^N, \quad p_a = 100 \text{ kPa}$$

Ulazni parametri za prikazanu jednačinu dati su u tabeli 1, a grafički prikaz Young-ovog modula elastičnosti u funkciji efektivnog vertikalnog napona – na Slici 6.

Clayey marl (CI-CH) medium to high plasticity, hard consistency, yellow to dark brown with the admixture of manganese and iron oxide and CaCO_3 in the form of powder and grains of cm-dimensions. The layer bulk density is $\gamma \approx 20.5 \text{ kN/m}^3$, cohesion $c' = 75.0 \text{ kPa}$. The layer extends to the bottom of the drillings, up to 35m from the ground surface.

The deformability parameters of the layers for numerical simulation were estimated on the results of field-laboratory testing. Bearing in mind the nonlinear relationship between the deformability parameter and the effective stress, the following equation is used (Duncan, 1980):

The input parameters for the equation are given in Table 1, and the graphic representation of the Young Modulus Module in the function of effective vertical stress is shown in Fig. 6.

Tabela 1. Parametri deformabilnosti slojeva
Table 1. Parameters of deformability of layers

	(n)	(ML-CL)	(SF-SC)	(CI-CH)
$E \text{ (MPa)}$	-	-	-	30.0
K	60.0	90.0	150.0	-
N	0.45	0.45	0.25	-
k_0	1.0	1.0	1.0	-
ν	0.33	0.30	0.33	0.33

Slika 6. Young-ov modul elastičnosti slojeva u funkciji efektivnog napona
Figure 6. Young's modulus of elasticity of layers in the function of effective stress

Nivo podzemne vode na lokaciji, tokom ispitivanja (jun 2015), bio je na dubini između 2.2–3.4 m od površine terena koji je u blagom padu ka jugoistoku, od 78.8 do 77.6 m nadmorske visine. Nivo podzemne vode je promenljiv, pa je za potrebe praćenja nivoa ugrađen jedan piezometar Ø50 mm, do dubine od 20 m. Najveći deo kvartarnih sedimenata zastupaju pesak i šljunak, koji se odlikuju međuzrnskom poroznošću i čine hidrogeološke rezervoare. U tim sedimentima formirana je slobodna izdan, čija je gornja granica u direktnoj hidrauličkoj vezi s Dunavom, pa se dubina podzemne vode – zavisno od nivoa Dunava – kreće od min. cca 1.0 m do max. cca 6.0 m. U podini ove izdani pojavljuju se sedimenti neogena, koji predstavljaju hidrogeološki izolator, a izgrađeni su od veoma malo propusnih laporovitih glina.

3 PRORAČUN ZAŠTITNE KONSTRUKCIJE OD AB DIJAFRAGMI I RAZUPIRAČA

Na osnovu analize različitih varijanti iskopa i razupiranja, odlučeno je da se – kao najpovoljnije rešenje – primene fazni iskopi temeljne jame, uz fazno razupiranje dijafragme.

Ceo proces iskopa i razupiranja pojednostavljeno je modeliran u geotehničkom softveru „GeoStudio” za ravansko stanje deformacija. Imajući u vidu veliku vodopropusnost slojeva, korišćena je analiza sa efektivnim parametrima u dreniranim uslovima. Analiziran je kritičan presek u kojem se nalazi postojeći zidani objekat koji vrši dodatno horizontalno opterećenje na AB dijafragmu. Program koristi metodu konačnih elemenata i inkrementalno-iterativni postupak za rešavanje sistema nelinearnih algebarskih jednačina. U modelu postoji ukupno 14 inkremenata, od kojih „Initial Insitu Stress” predstavlja inicijalno naponsko za definisanje nelinearnih parametara deformabilnosti u funkciji napona, dok se u „Temelj RKC” unosi uticaj postojećeg objekta.

The groundwater level at the site (June 2015) was at a depth of 2.2-3.4m from the ground surface, which is slightly inclined to the southeast from 78.8-77.6m. The ground-water level is variable, so a Ø50mm piezometer up to a 20m depth is installed to monitoring purposes. Most of the quaternary sediments are represented by sand and gravel, which are distinguished by integranular porosity and make up hydrogeological reservoirs. In these sediments, a free issue is formed, whose upper limit is in direct hydraulic connection with the Danube, so the depth of the groundwater depending on the Danube level ranges from min. 1.0m to max. 6.0m. In the bottom of this issue, sediments of Neogene's representing a hydrogeological isolator are present, built from very low permeable clayey marl.

3 THE DESIGN OF THE RC DIAPHRAGM WALLS AND STRUTS

Based on the analysis of various variants of excavation and bracing, it was decided to use the phase digging and bracing of the diaphragm wall as the most favourable solution.

The entire process of digging-bracing is simplified and modelled in the geotechnical software "GeoStudio", for plane deformation state. Considering the high permeability of the layers, the analysis with effective parameters in drained conditions was used. A critical cross-section in which the existing masonry is located, which performs additional horizontal load on the AB diaphragm wall, has been analyzed. The program uses the finite element method and an incremental-iterative procedure for solving the system of nonlinear algebraic which the "Initial Insitu Stress" represents an initial stress for the definition of non-linear deformability equations. The model has a total of 14 increments, of parameters in the function of stress, while the "RKC"

Slika 7. Pojedinačna stanja (inkrementi) definisani u numeričkom modelu za „GeoStudio”
Figure 7. Partial states (increments) defined in numerical model for the GeoStudio

Po završetku AB dijafragme, prvo se radi širok iskop (cca 4.100 m²) do dubine od 4 m, što je približno oko 0.5 m iznad trenutnog nivoa podzemne vode, kako bi se formirao radni plato na koti 75 m. U numeričkom modelu, to je „Iskop-1”.

S radnog platoa urađena su dva bunara, do sloja laporovite gline, kapaciteta 15l/s, za crpljenje i snižavanje nivoa podzemne vode unutar temeljne jame. Nakon što je nivo podzemne vode u roku od približno tri nedelje snižen na oko 0.5 m ispod dna konačnog iskopa, pristupilo se iskopu do kote 69.5 m, s privremenom bermom uz dijafragmu. U numeričkom modelu, ovo stanje jeste „Iskop-6”, a predloženo je na Slici 8.

enter the influence of the existing object. At the end of the diaphragm wall execution, a wide excavation (approx. 4,100m²) is completed to a depth of 4.0m, which is about 0.5m above the current groundwater level, in order to form a working plateau a level of 75.0m. In the numerical model, this increment is "Iskop-1".

From the working plateau, 2 wells were made, to a layer of clayey marl, with capacity of 15 l/s, for pumping and lowering the level of groundwater inside the foundation pit. After its lowering to about 0.5m below the bottom of the final excavation, within approximately 3 weeks, a digging up to the level of 69.5m, with a temporary berm in front of diaphragm wall, has begun. In the numerical model, this state is "Iskop-6", and is shown in Fig. 8.

Slika 8. Privremeno stanje s bermom, nakon iskopa do dna temeljne jame
 Figure 8. Temporary condition with berm after excavation to the bottom of the pit

Snižen nivo podzemne vode i privremena berma omogućuju izradu dela temeljne ploče, na kojoj se gradi podzemni deo konstrukcije. Uklanjanje berme radi se postupno, nakon postavljanja razupirača između dijafragmi i izgrađenih elemenata konstrukcije (stubovi i ploče) podzemnog dela objekta. Privremeno stanje, nakon postavljanja čeličnog razupirača i potpunog uklanjanja berme, prikazano je na slici 9.

The lower groundwater level and the temporary berm allow the execution of the part of the foundation slab. The berm is removed gradually after the placement of the struts between the diaphragm wall and between the diaphragm wall and the built elements of the structure (columns and slabs) of the underground part of the building. The temporary state after installation of the struts and complete removal of the berm is shown in Fig. 9.

Slika 11. Horizontalno pomeranje dijafragme tokom iskopa i razupiranja
Figure 11. Horizontal displacement of the d-wall during excavation and bracing

Slika 12. Sleganje zaleđa dijafragme tokom iskopa i razupiranja
Figure 12. Settlements behind the d-wall during excavation and bracing

Razupiranje se radi čeličnim cevima $\varnothing 600$ mm, koje se vare na čelične HOP-podvlake koje su zavarene za ubušene ankere $\varnothing 22$ u dijafragmu. Na mestu gde je temeljna jama najšira (36m), umesto čelične cevi postavljen je razupirac od čelične rešetke.

The bracing is done with $\varnothing 600$ mm steel tubes, which are applied to steel beam underlays welded to battered $\varnothing 22$ mm anchors in the diaphragm wall. At the point where the width of the pit is the largest, up to 36m, instead of pipe, the steel trust grid is laid out. The

Proračunom su određeni svi relevantni podaci za dimenzionisanje i procenu stanja – kao što su momenti savijanja u dijafragmi i pomeranje dijafragme, sila u razupiraču, pomeranje i sleganje terena ispod postojećeg objekta u zaleđu dijafragme i tome slično.

Maksimalni računski moment savijanja jeste 180 kNm u zaleđu, a 230 kNm u pročelju dijafragme. Maksimalno horizontalno računsko pomeranje dijafragme je 34 mm, a najveće pomeranje izmereno geodetskim instrumentom jeste oko 40 mm. Maksimalno računsko sleganje zaleđa zida je oko 32 mm, dok je geodetski izmereno maksimalno sleganje oko 21 mm. Maksimalna računska sila u razupiraču jeste 280 kN/m.

calculation in GeoStudio determines all relevant data for dimensioning and assessment of the condition, such as the bending moments and the displacement of the diaphragm wall, the force in the strut, the displacements and settlements of the terrain beneath the existing object in the back of the diaphragm wall, and others.

The maximum bending moment is 180kNm in the back of d-wall and 230kNm in front of it. The maximum horizontal computed movement of the d-wall is 3.4cm, and the maximum movement measured by the geodesic survey is about 4cm. The maximum settlement behind the d-wall is about 3.2cm, while the measured movement occurred by geodesic survey is about 2.1cm. The maximum estimated force in the strut is 280 kN/m.

Slika 13. Sila u razupiraču tokom iskopa
Figure 13. Strut axial force during the excavation

4 KRATAK PRIKAZ IZVOĐENJA RADOVA

Iskop temeljne jame rađen je fazno, u vertikalnom i horizontalnom smislu. Vertikalna faznost prikazana je u prethodno opisanom računskom modelu. Horizontalna faznost bila je neophodna zbog toga što su se razupirači oslanjali ne samo na dijafragme međusobno, već i na izvedene delove podzemne konstrukcije. Načelno, bilo je pet (V) horizontalnih faza iskopa s razupiranjem, koje su - u periodu od oko 6-7 meseci – omogućile da se kompletira temeljna ploča na poslednjoj fazi, pri čemu je na prvoj fazi objekat završen približno do nivoa 5. sprata.

4 SHORT DESCRIPTION OF THE WORKS

The excavation of the foundation pit has been carried out in phases, in a vertical and horizontal sense. Vertical phases is shown through the previously described computational model. Horizontal phases was necessary because the struts relieved not only between the diaphragm wall, but also on the derived parts of the underground structure. In principle, there were five (V) horizontal excavation phases, which in the period of about 6-7 months, enabled the foundation slab to be completed at the last stage, with the first stage being completed approximately to the level of 5 floors.

Slika 14. Razupirači – oslonjeni samo na dijafragme u I fazi (10.05.2017)
Figure 14. The struts relying on RC diaphragm wall in phase-I (10.05.2017)

Slika 15. Razupirači i armatura temeljne ploče u I fazi (21.05.2017)
Figure 15. The reinforcements of the foundation slab in phase-I (21.05.2017)

Prva faza obuhvatila je krajnji severoistočni deo građevinske parcele, na kojoj se pojavljuje stambena jedinica spratnosti P+8(9). To je najuži deo lokacije, koji je omogućio da se izvrši razupiranje dijafragme o dijafragmu, preko čeličnog razupirača (najduže – 27.5 m). Radi ravnomernijeg prijema sile s podvlake, razupiraču su dodati bočni kosi kraci. Na slikama su vidljiva mestimična procurivanja vode na spojevima dijafragmi, koji se injektiraju epoksidnim smolama pre postavljanja hidroizolacije. Takođe, uz dijafragme, uočava se povijena hidroizolacija iz temeljne ploče.

The first phase included the far north-eastern part of the building plot, where the housing unit P+8 appears. It is the closest part of the site, which enabled the diaphragm wall to be pulled out, through a steel pipe, with the largest length up to 27.5m. For the even reception of the force from the walls, the lateral pieces are added to the pipes. In the pictures, there are visible spots of water leaks on the diaphragm wall joints, which are injected with epoxy resins prior to the installation of waterproofing. Also, along the walls, bended waterproofing from the slab is visible. The waterproofing

Hidroizolacija se lepi za betonsku površinu, a nastavlja se na preklop, uz specijalni lepak. Na prednjem delu slike 16 vidi se razupiranje dijafragme o stub izgrađenog dela konstrukcije.

is adhered to the concrete surface and continues to the transition with a special adhesives. The struts between diaphragm wall and built column of the structure appear at the lower front of Fig. 16.

Slika 16. Razupirači oslonjeni na dijafragme i delove konstrukcije u II fazi (21.06.2017)
Figure 16. Struts relying on d-wall and on the part of construction in phase-II (21.06.2017)

U fazi III – zbog velike širine temeljne jame – odlučeno je da se razupiranje izvrši čeličnom četvoropojasnom rešetkom od starog kрана koji je dlimično nadograđen (slika 17.). Na istoj slici, u levom uglu je detalj razupiranja o postojeći stub konstrukcije, dok se u desnom uglu nazire deo neuklonjene peščane berme.

In phase III, due to the great width of the foundation pit, it was decided to brace it with steel four-lane grid from the old crane, which was gradually upgraded (Fig. 17). In the same picture, in the left corner is the detail of the strut between the column and the wall, while in the right-hand corner there is a part of the un removed sand berm.

Slika 17. Razupiranje četvoropojasnom čeličnom rešetkom od 36 m u III fazi (08.07.2017)
Figure 17. Strutting with 36m long steel grid at phase-III (08.07.2017)

U donjem levom delu slike 17. vide se nadzemni deo bunarske konstrukcije i potisni cevovod od aluminijumske cevi Ø100 mm. Iskop u temeljnoj jami rađen je sve vreme manjim bagerima, smeštenim na dnu temeljne jame, koji su materijal prebacivali do kašike bagera na višem nivou, koji je potom pesak tovario u kamione koji su išli na izlaz u ulici Narodnih heroja.

The above-ground part of the well structure and the alkaline Ø100mm pipeline appear in the lower left part of Fig. 17. The excavation in the foundation pit was carried out all the time with smaller excavators that were at the bottom of the underground pit. The material was transported by the bucket of the excavator on a higher level where the sand was loaded into trucks and moved to the exit in the Narodnih heroja street.

Slika 18. Završni zemljani radovi i razupiranje u IV i V fazi (03.11.2017)
Figure 18. Final earthworks and strutting at phase IV-V (03.11.2017)

Slika 19. Radovi na nivou 2 u IV i V fazi (12.12.2017)
Figure 19. Works at level-2 at phase IV-V (12.12.2017)

Radovi na iskupu ispod radnog platoa, na koti 75.0 m, započeti su krajem aprila 2017. godine, a poslednja kašika bagera utovarena je zemljom iz iskopa početkom novembra 2017. Praktično, u periodu od maja do oktobra 2017. godine, završen je iskop oko 37.000 m³ zemlje, a istovremeno je završeno i razupiranje dijafragme međuspratnim pločama, tako da su uklonjeni svi privremeni čelični razupirači.

5 ZAKLJUČAK

U radu je prikazan način proračuna i izvođenja zaštitne konstrukcije za duboku temeljnu jamu i susedne objekte, u složenim urbanim i geotehničkim uslovima, korišćenjem relativno jednostavne tehnike, koja podrazumeva paralelnu gradnju i razupiranje o izvedene delove objekta. Ovim postupkom, izbegnuta je potreba da se izradi veći broj šipova velikog prečnika, koju zahteva „Top-Down” metoda, odnosno izrada velikog broja prednapregnutih sidara.

Osim dijafragme, sve podzemne radove na iskupu i razupiranju, izvela je građevinska firma – koja je ujedno bila i investitor, i to isključivo korišćenjem standardne građevinske opreme i radne snage. Ovakav postupak potpuno je odgovarao izvođaču radova – i u pogledu vremena i u pogledu dinamike korišćenja raspoloživih sopstvenih materijalnih i ljudskih resursa.

Radovi na izgradnji podzemnog dela objekta protekli su bez problema, a izmerena pomeranja dijafragme u granicama su računskih pomeranja. Na starim susednim objektima, u toku iskopa, pojavila su se manja oštećenja u vidu prslina u zidovima i tavanicama, što je prouzrokovano neizbežnim sleganjem tla u zaleđu dijafragme. Međutim, nivo oštećenja susednih objekata bio je u očekivanom opsegu, pa će nastala oštećenja po završetku radova biti otklonjena o trošku izvođača.

6 LITERATURA REFERENCES

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Work on the excavation under the working plateau at 75.0m began at the end of April 2017, and the last bucket of excavator was loaded with excavated soil in early November 2017. Basically, over the period of time from May to October 2017, the excavation of about 37,000m³ of soil was carried out and simultaneously the struts on the diaphragm wall were replaced with the reinforced slabs of the construction.

5 CONCLUSIONS

This paper presents the method of calculation and execution of a protective structure for a deep foundation pit and adjacent objects, in complex urban and geotechnical conditions, using a relatively simple technique, which implies parallel construction and bracings from the constructed parts of the object. This procedure avoided the need of number of large-diameter piles by the “Top-Down” method, or a large number of prestressed anchors.

Instead of the diaphragm wall, all underground excavation and bracing works were carried out by a construction company, which was also an investor, by using standard construction equipment and labour. This procedure was fully in line with the contractor, both in terms of time and dynamics of using available own material and human resources.

Works on the construction of the underground part of the building have passed without any problems, and the measured diaphragm wall movements are within the limits of calculation shifts. In the old neighbouring buildings, minor damages in the form of cracks in the walls and ceilings occurred during the excavation, which was caused by the inevitable settlement of the soil behind the diaphragm wall. However, the level of damage to adjacent objects was in the expected range, and after the building will be finished, all damage will be removed at the expense of the contractor.

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REZIME

PRIMER ZAŠTITE DUBOKE TEMELJNE JAME I SUSEDNIH OBJEKATA U SLOŽENIM URBANIM I GEOTEHNIČKIM USLOVIMA

Željko BAJIĆ
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Prilikom izgradnje novih objekata s više podzemnih etaža, u urbanim sredinama, poseban problem predstavlja zaštita dubokih temeljnih jama i susednih objekata, posebno kada je reč o starim, plitko fundiranim i zidanim objektima koji nemaju adekvatna ukrućenja vertikalnim i horizontalnim serklažima. Ako se na postojeći problem nadovežu i složeni geotehnički uslovi, u vidu visokog nivoa podzemne vode, velike vodopropusnosti sredine i blizine reke koja je u hidrauličkoj vezi s lokacijom, problem izgradnje podzemnog dela objekta po složenosti može višestruko prevazići složenost izgradnje nadzemnog dela.

U ovom radu prikazan je upravo jedan vrlo složen problem zaštite duboke temeljne jame za trospratnu podzemnu garažu stambeno-poslovnog objekta „Pupinova palata“ u Novom Sadu, na Bulevaru Mihajla Pupina, ukupne površine oko 43.000 m², i vrlo razuđene spratnosti. Na građevinskoj liniji budućeg objekta bili su višespratni, stari, plitko temeljeni i zidani objekti. Nivo podzemne vode na lokaciji bio je relativno visok, u direktnoj hidrauličkoj vezi s rekam Dunav – udaljenoj oko 800 m - i velikim doticajem podzemne vode kroz vodopropusne i lako pokretljive sedimente dunavskog peska.

Analizirano je više idejnih varijanti zaštitne konstrukcije, razmatrane su prednosti i nedostaci rešenja, a detaljno je opisano usvojeno rešenje zaštite temeljne jame i susednih objekata. U trenutku pisanja ovog članka, podzemni deo objekta uspešno je završen, a rezultati izmerenih pomeranja zaštitne konstrukcije bili su u granicama računskih.

Ključne reči: duboka temeljna jama, armirano-betonska dijafragma, numerička simulacija

SUMMARY

EXAMPLE OF PROTECTION OF DEEP FOUNDATION PIT IN COMPLEX URBAN AND GEOTECHNICAL CONDITIONS

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In the construction of new buildings with several underground floors, in urban areas, a special problem is the protection of deep foundation pit and adjacent structures, especially when it comes to old, shallow and masonry structures that lack adequate stiffness. If complex geotechnical conditions are met, in the form of high groundwater level, high water permeability of the soil, and proximity of the river, which is in a hydraulic connection with the site, the complexity of building underground part can be overcome in many ways over the complexity of the above-ground construction. This paper presents a very complex problem of protecting the deep foundation pit for the three-storey underground garage of the residential and business building "Pupin's Palace" in Novi Sad, in Boulevard Mihajla Pupina, with total area of about 43,000m², and very diluted floors. On the construction line of the future facility were multi-storey, old, shallow-grounded and masonry buildings. The groundwater level at the site was relatively high, in a direct hydraulic connection with the Danube river, which is about 800m away, and a large subterranean water supply through the permeably and easily mobile sediments of the Danube sand. Several conceptual designs of the protective structure were analyzed, the advantages and disadvantages of the solution were considered, and the adopted solution for protection of the foundation pit and adjacent objects was described in detail. At the moment of writing this article, the underground part of the building was successfully completed, and the results of the measured shifting of the protective structure were within the estimated limits.

Key words: deep foundation pit, reinforced concrete diaphragm wall, numerical simulation