EFFECT OF THE PERMANENT DEWATERING ON THE NEIGHBORING BUILDINGS AT “PROMENADE SHOPPING MALL”

Petar Santrač[1]
Ognjen Gabrić[2]
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Summary: *This paper contains the results of the numerical simulation of the groundwater level lowering outside the diaphragm wall and terrain subsidence, due to permanent dewatering below the building of “Promenade Shopping Mall”. The project solution provided that, instead of waterproofing, beside RC diaphragm wall and under a thick foundation slab which can sustain high upward water pressure, a permanent drainage system is made. The results of the numerical simulations, for the worst scenario, have generally shown that the maximum groundwater reduction at a distance of 31-64 m from the RC diaphragm wall is between 1.2-0.6 m. The corresponding size of the terrain subsidence in the zone of the closest buildings, as a result of an increase in the effective stress in the soil, due to a fall in the groundwater level, is between 5.4-2.7 mm.*

Keywords: *dewatering, groundwater, subsidence*

1. INTRODUCTION

The “Promenade Shopping Mall” building is located in Novi Sad, Republic of Serbia, near the crossing of “Boulevard Cara Lazara” and “Boulevard Oslobodjenja”, on the cadaster parcel 900/18 at Cadastral Municipality Novi Sad II.
Beneath the building, the permanent dewatering system was built. According to the data obtained from the Contractor [1] of underground works, during the excavation of the foundation pit, the number of active wells was 12. After the vertical curtain of RC diaphragm wall was built around the pit of 32,000 m^2, the number of active wells, due to the reduced groundwater inflow is minimized. At the beginning of 2018. number of active wells is 4: DW4, DW5, DW9 and DW12 (Fig. 1).

1 Petar Santrač, PhD, CE, University of Novi Sad, Faculty of Civil Engineering Subotica, Kozaračka 2a, Subotica, e-mail: ogabric@gf.uns.ac.rs
2 Ognjen Gabrić, PhD, CE, University of Novi Sad, Faculty of Civil Engineering Subotica, Kozaračka 2a, Subotica, e-mail: ogabric@gf.uns.ac.rs

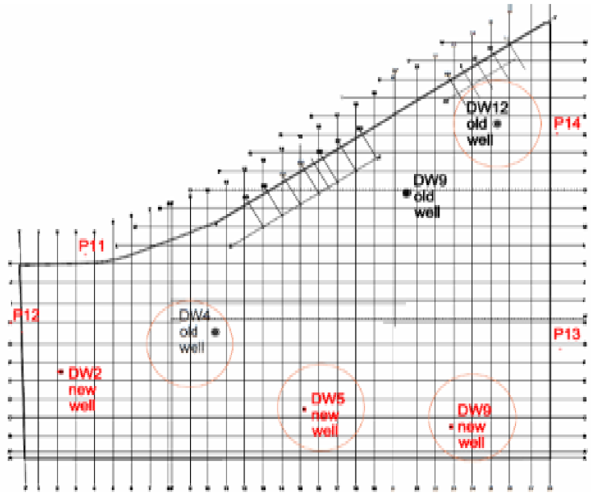

Figure 1. Locations of the dewatering wells (DW) and piezometers (P)

Outside the foundation pit, the groundwater level during dewatering was measured with 4 piezometers (P11, P12, P13 and P14), which are located directly to the outside of reinforced concrete (RC) diaphragm wall (Fig. 1). The wall thickness is 60 cm and the pit perimeter is 800 m.

Primary morphology of the site has been changed by the influence of the urbanization process. Existing terrain has a slight decline in the northeast-east direction, with an altitude between 76.5-78.2 MASL. Deeper layers are built up by quaternary sediments of Holocene ages through sedimentary Neogene’s (Pliocene). Most of the quaternary are sand and gravel, which are distinguished by intergranular porosity and form a hydro-geological reservoir. In these sediments, a free water level is formed. It is in direct hydraulic connection with the Danube river, which primary influence the groundwater level at the location.

Below the hydrogeologycal reservoir, Neogene sediments are provided in the form of clayey marl of Pliocene age, with very low permeability.

The altitude of the practicaly impermeable marl layer is betwen 49.0-45.0 MASL, which is higher than the bottom of the RC diaphragm wall. The depth of the underground parking garage is around 6.8 m, which corespond to the altitude of 70.6 MASL. During the utilisation of the object, the groundwater level below the foundation slab, will be maintain at the same level (70.6 AMSL).

During the geotechnical investigation [2, 3] (August 2016), the groundwater level was between 73.7 and 75.1 MASL. Based on measurements [4] in piezometers on the territory of Novi Sad, the maximum groundwater level at the site is about 76.0 m.

The project solution provided that, instead of waterproofing, beside RC diaphragm wall and under a thick foundation slab which can sustain high upward water pressure, a permanent drainage system is made. Above the drainage where the level of groundwater is maintained, a relatively thin RC slab (15 cm) is predicted. In this way, a passive groundwater protection is replaced by an active one with no possibility to sustain

uppward water pressure, which only collect the infiltrated groundwater by drainage wells and pump into the sewerage.
In order to minimize the infiltration of groundwater, RC diaphragm walls are lowered to the second, lower layer of marble clay, at a depth of about 35 m below the terrain surface. In the phase of pit excavation, RC diaphragm walls protect the working space and limit the large inflow of groundwater, while during the exploitation of the facility, they should maintain the natural groundwater level in the immediate environment.
The estimate was that the amount of water flowing from the bottom and partly through the joints of the diaphragm walls would be about 5-7.0 l/s. However, after closing the curtain from RC diaphragm walls, it was found that the amount of infiltrated water is around 15-17.0 l/s.
Because of the larger infiltration, the question was set, of the influence of pumping inside the embracing area on the natural groundwater level in the immediate environment, the induced subsidence of the terrain and it's influence on the neighboring objects. For the purposes of such an analysis, the Contractor has supplied available documentation for installed wells and piezometers as well as appropriate measurements in them, as a basis for the development of a hydraulic model. This model would assess the lowering of the groundwater level outside the diaphragm walls compared to the natural level, and as a result, the subsidence of the terrain and it's possible impact on the adjacent objects.
In order to give a realistic prediction, the most important for model is its calibration based on data obtained by quality simultaneous over time measurements of all relevant impacts, such as inflow in wells, water levels in wells and piezometers, natural groundwater level, Danube level and precipitation (rain, snow). Unfortunately, most of these data was unreliable, due to which certain operating assumptions have to be introduced into the calculation, based on which, instead of an explicit result, the upper limit of the groundwater lowering and subsidence of the terrain and the most unfavorable impacts on the objects are obtained.

2. AVAILABLE DATA

Among the whole set of data of water level measurements in wells and piezometers, only data obtained by measurements during January and February 2018 were used for further analysis. The data collected during 2017 are not useful. Some wells worked occasionally, some of the existing ones were destroyed, in the meantime new one was added and the degree of the diaphragm walls completion were not fully known. In 2018, the diaphragm wall was finished. Among previous, the water level in the wells and in the piezometers in time are known, as well as individual flows from wells, but not the initial hydraulic state. However, this data sims more useful than the formers in 2017.

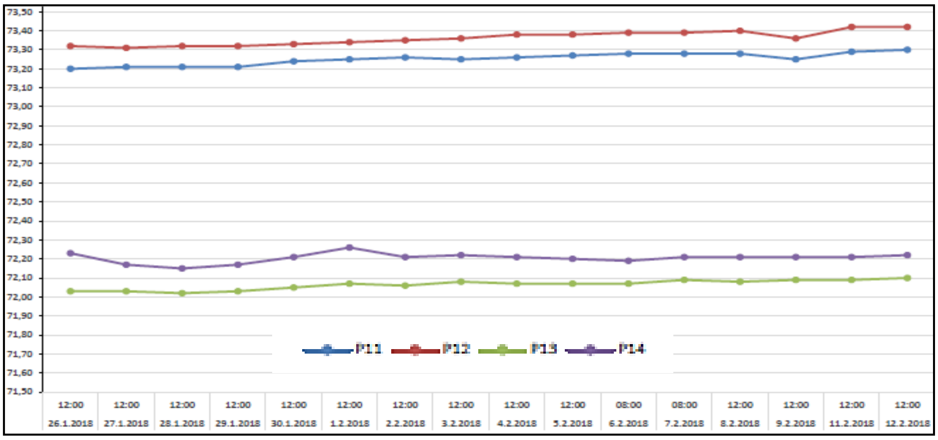

Figure 2. Water level in outside piezometers P11-P14 (Jan.01 - Feb.12.2018.)

Figure 2 [5] shows the results of measuring the water levels in the piezometers. during the pumping of water from 4 active wells (DW4, DW5-new, DW9-new and DW12), with a total flow of 17.32 l/s (about 1,500 m^3/day). Figure 3 [5] shows the results of measuring the levels in the wells, during the pumping of water from 4 active wells (DW4, DW5-new, DW9-new and DW12).

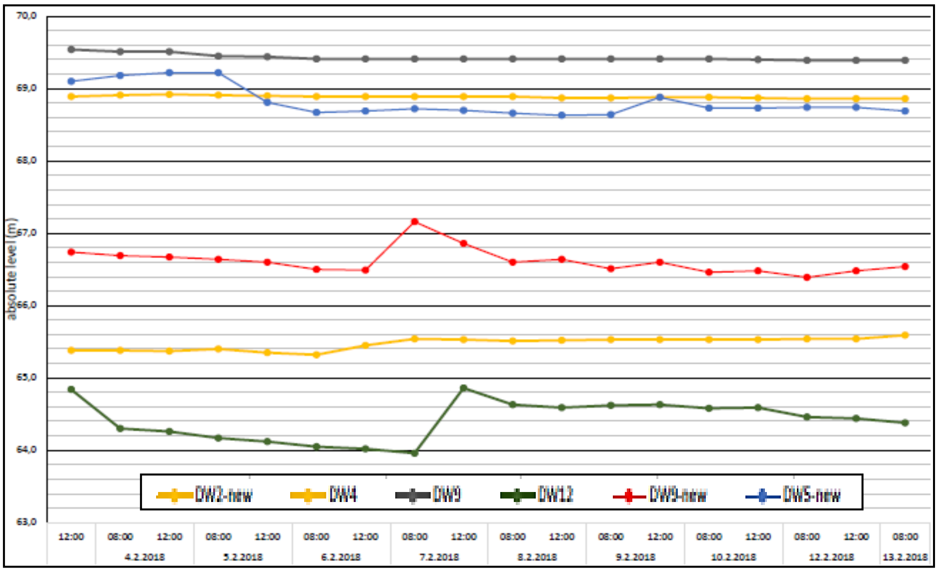

Figure 3. Water level in dewatering wells (Jan.28 - Feb.13.2018.)

Table 1. Wells efficiency during water pumping (l/s) [6]

Date / Well №	DW4	DW5 + DW9	DW12	Total
Feb. 13.2018	6.11	3.57	7.64	17.32

Analyzing the obtained curves, it can be concluded that it corresponds to a steady regime, which is characterized by relatively flat levels, with time-related jumps and falls that are most likely associated with pump interventions. It is also impossible to exclude the influence of natural factors, such precipitation, and the most pronounced, the water level of the Danube [7] river (Figure 4).

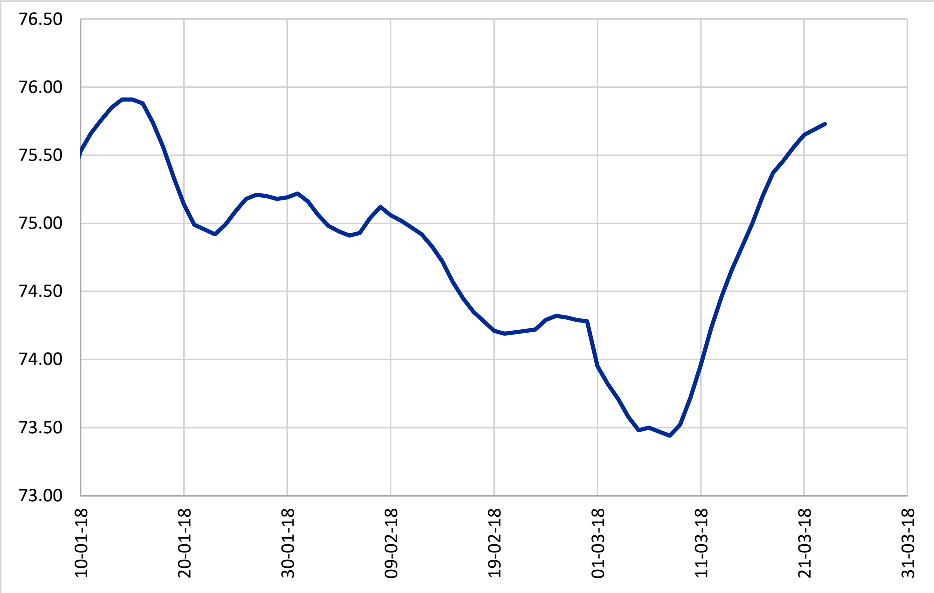

***Figure 4**. The water level of the Danube at Novi Sad[8] – 2018*

Figure 4 shows the water level of the Danube in the first 3 months in 2018, which clearly shows that during the measurement of the water level in the wells and piezometers, there was a constant, almost linear fall of the level by about 2.0 m. The data listed in this chapter (2) are partly used for the calibration of the hydraulic numerical model, which will be described in the next chapter (3).

3. HYDRAULIC NUMERICAL MODEL

Hydraulic analysis is performed using commercial software “MODFLOW” which uses finite differences method to determines the water flow in a three-dimensional, inhomogeneous, anisotropic and saturated (or unsaturated) porous medium. The numerical model is based on the solution of partial differential equations of the form:

$$k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} + k_z \frac{\partial^2 h}{\partial z^2} + W = S_s \frac{\partial h}{\partial t} \qquad h = z + \frac{u}{\gamma_w}$$

where: k_x, k_y, k_z, is the soil water-permeability in x, y, z direction, h is the potential of the hydraulic field (geodetic + pressure), t is the time, W is the variable connected to a hydraulic source, and S_s is the specific storage of the aquifer.

In order to assess the most unfavorable influences due to dewatering, a numerical model was created which, based on the available data, provides an image of the size of the groundwater lowering at a wider location around the facility.

The model calibration was based on available data, such as hydraulic measurements in the wells and piezometers on site, geomechanical profiles obtained by site investigation, permeability of soil layers obtained by field and laboratory permeability tests and correlation based on soil granulometric composition, as well as experience data from locations [8, 9, 10, 11] in Novi Sad.

It is realistic to expect water to enter from the underlying ground, infiltration through the diaphragm wall joints and precipitation. However, since it is impossible to determine the share of individual inflows, the lowering of groundwater in the zone of adjacent objects is determined under the conservative assumption, that the water in the wells inflow exclusively through the diaphragm wall joints. It is not difficult to conclude that the previous assumption, for given flow in wells, gives a max reduction of groundwater level outside the diaphragm wall.

The permeability of the diaphragm wall is determined iteratively, by matching the measured water levels in wells and piezometers inside the foundation pit [12] during 2017-2018, and the actual outside groundwater level of around 74.0 MASL, with the calculated levels in wells and piezometers obtained by the numerical model. The iteratively obtained permeability of the diaphragm wall is around 10^{-2} m/day.

The parameter that also significantly influences the hydraulic current image is a natural and time-varying groundwater level. However, this information is missing. What is reliably known is the maximum groundwater level at a location of about 76.0 MASL and statistical data for the water level of the Danube in Novi Sad during the year.

Hydraulic conditions for solving differential equations of unsteady flow, which were inputted into commercial software “MODFLOW”, are the following:

a) The altitude of the terrain, which is between 76.5-78.2 MASL, is adopted at average value of 77.5 MASL. The depth of the pit which is about 6.8 m, corresponds to altitude of 70.6 MASL.
b) The groundwater level on the outermost boundary of the site is adopted from the regime of low (74.0 MASL), medium (75.0 MASL) and high (77.0 MASL) water levels on Danube river. These levels are set successively as constant value from a radius of 1.0 km around the center of the site.
c) The aquifer floor is set to the altitude of upper surface of marble clay, at 45.0 MASL. The marble clay layer is assumed in modeling as waterproof barrier.
d) The bottom of the diaphragm wall is penetrated into marble clay layer. The iteratively obtained permeability of the wall is 10-2 m/day, or at around 10-7 m/s.
e) Dewatering wells are of perfect type, with 8.0 m long filter part.

f) The water level inside the wall is maintained at the altitude between 70.0-70.6 MASL.
g) The pumping rate is constant (around 1,500 m3/day, 1,700 m3/day and 1,900 m3/day, for the initial groundwater level of 74.0 MASL, 75.5 MASL and 77.0 MASL, through the period of 300 days).

The results of successive numerical simulations/calculations, using 3 different initial groundwater levels over boundary of the site, are presented graphically on figures 5, 6 and 7.

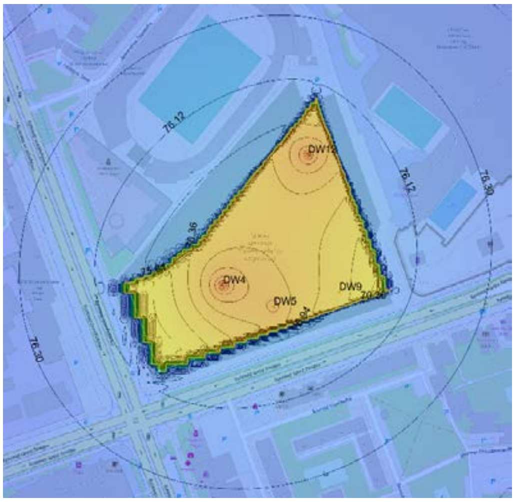

Figure 5. Groundwater altitudes arround the site for boundary level of 77.0 MASL

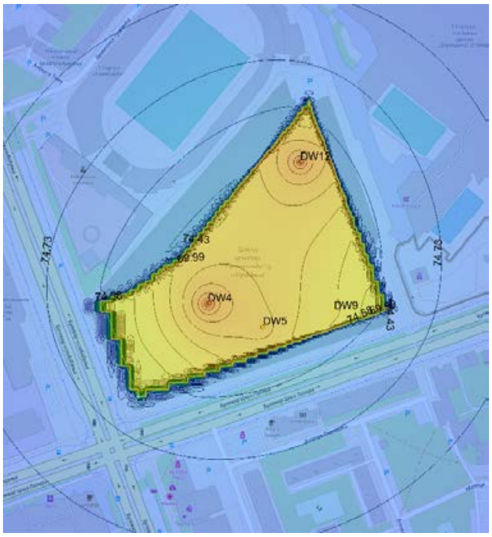

Figure 6. Groundwater altitudes arround the site for boundary level of 75.5 MASL

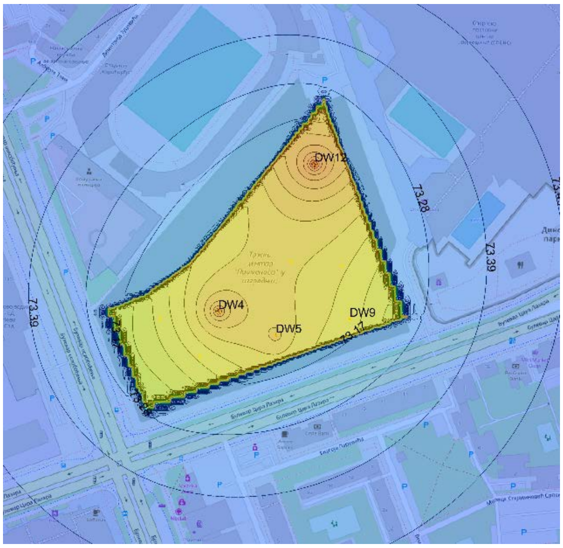

Figure 7. Groundwater altitudes arround the site for boundary level of 74.0 MASL

4. GEOTECHNICAL NUMERICAL MODEL

Lowering the groundwater level causes a decrease in the pore-water pressures and an increase in effective stresses which press the soil skeleton and cause subsidence of terrain and settlements of neighboring buildings. The size of the subsidence and settlements of buildings, primarily depends from the size of groundwater lowering and the compressibility of the soil.

In routine geotechnical practice, the compressibility of the cohesive soils samples is mainly estimated by laboratory tests (unconfined modulus of deformation), while for non-cohesive soils layers (sand and gravel) by penetration test (CPT, SPT, DMT). Since the geomechanical profile of the site around the “Promenade Shopping Mall” is built from sands and clayey and silty sands, the deformation parameters for the calculation of ground subsidence due to groundwater lowering are determined from the results of static penetration tests (CPT).

Subsidence of the terrain due to groundwater lowering in the soil can be simply estimated by the method of one-dimensional deformation, based on the following expression:

$$s = \int_{z_1}^{z_2} \varepsilon_z dz = \int_{z_1}^{z_2} \frac{\Delta\sigma'_z}{E_s} dz$$

where: Δσz is the increase of vertical effective stress in the soil layer, E_s is the soil layer deformation parameter z_2-z_1 is the thickness of the soil layer exposed to change in effective stress.

The increase of effective vertical stress in the soil, due to groundwater lowering for ΔH, and the corresponding terrain subsidence is:

$$\Delta\sigma'_z = \gamma_w \cdot \Delta H \;\rightarrow\qquad s = \int_{z_1}^{z_2} \frac{\gamma_w \cdot \Delta H}{E_s} dz$$

In the above equation, the γ_w is the water volume weight, and ΔH is the groundwater drop.
Based on the results of penetration tests, the cone resistance shows roughly linear increase with depth, which can be expressed as $q_c=\beta\cdot z$, where is $\beta\approx900$ kPa/m. The sandy layer which is under deformation roughly extent from z=4.0 m up to 22.0 m, to the contact with clayey marl, under which the soil can be assumed as practically un-deformable.
The deformation modulus of the sandy layer, using the α-approximation method based on static penetration test can be expressed as: $E_s=\alpha\cdot q_c$. For sands and mostly sandy soils the α-value is about 4.

5. RESULTS

The results of hydraulic analysis have shown, that the relative drop of the groundwater level, at the identical locations around the "Promenade Shopping Mall", decrease slightly when lowering the initial groundwater altitude.
The nearest buildings around the site are between 31-64 m. For the initial groundwater level of 77.0 MASL, the relative drop is from 1.2 m for the nearest distance, to 0.8 m for the farthest distance.
For the initial groundwater level of 75.5 MASL, the relative drop at the identical locations is from 1.1 m to 0.7 m, while for the initial groundwater level of 74.0 MASL, the results is from 0.9m to 0.6m.

Table 2. Results of the terrain subsidence caused by groundwater lowering

Type and location of the nearest building	Distance from the building "Promenade Shopping Mall"	Initial groundwater altitude		
		77.0 MASL	75.5 MASL	74.0 MASL
	(m)	Terrain subsidence s(mm)		
North of the site	31.0	5.4	5.0	4.1
East of the site	46.0	4.1	3.6	3.2
South o the site	57.0	4.1	3.6	3.2
West of the site	64.0	3.6	3.2	2.7

Analyzing the obtained results of the hydraulic numerical simulation/calculation, one should bear in mind that they relate to the worst scenario, which is not realistic. The results are conservative, and as such, they will give the upper limit of the subsidence of the terrain and settlements of the buildings.

Using the value of groundwater drop, the terrain subsidence is calculated and results is presented in table 5. Analyzing the obtained results, one should again bear in mind, that they relate to the worst scenario, which is not realistic, so the obtained subsidence of the terrain is highly conservative and give the upper limit.

6. DISCUSSION

This paper contains the results of numerical simulations of the groundwater levels outside the diaphragm wall and terrain subsidence, due to groundwater lowering below the building of “Promenade Shopping Mall”.
Because the lack of exact information through the time, the worst possible scenario has been analyzed. It is assumed that the whole inflow into the drainage wells, in the amount of about 1,500 m^3/day came only from infiltration through the diaphragm wall. This assumption gives the greatest possible lowering of the groundwater level outside the diaphragm wall and also the greatest terrain subsidence and settlements of neighboring buildings.
As a result of calculations, the maximum groundwater reduction, at a distance of 31-64 m, between the nearest buildings and diaphragm wall is 1.2-0.6 m. This is significantly less than the natural oscillations of the groundwater at the site.
The corresponding terrain subsidence in the zone of the closest buildings, as a result of an increase in the effective stress in the soil, due to a fall in the groundwater level, is between 5.4-2.7 mm.
Bearing in mind the constructive system of the neighboring buildings (RC skeleton or masonry with vertical and horizontal RC stiffening beams) and the estimated size of terrain subsidence, it is concluded that the pumping of groundwater from the drainage system inside the RC diaphragm embracing area, does not have an important and measurable adverse effects on the neighboring buildings.

Acknowledgements
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UTICAJ PERMANENTNOG ODVODNJAVANJA NA OBJEKTE U OKOLINI TRŽNOG CENTRA "PROMENADA"

Summary: *U radu su prikazani rezultati numeričke simulacije obaranja nivoa podzemne vode izvan zidova dijafragme i sleganje okolnog terena usled stalnog odvodnjavanja podzemne vode ispod temelja tržnog centra "Promenada". Projektnim rešenjem je predviđeno da se, umesto postavljanja hidroizolacije i relativno debele temeljne ploče koja može da podnese jake vertikalne sile uzgona, objekat štiti stalnim odvodnjavanjem. Rezultati numeričkog proračuna, za najnepovoljniji scenario, ukazuju da je maksimalno snižavanje nivoa podzemne vode na rastojanju od 31-64 m od dijafragme između 1.2 i 0.6 m. Odgovarajuće sleganje u zoni najbližih objekata, kao rezultat povećanih efektivnih napona u tlu, usled obaranja nivoa podzemne vode, iznosi 5.4-2.7 mm.*

Keywords: *odvodnjavanje, podzemna voda, sleganje*