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HIDRAULIČKA MODELSKA ISPITIVANJA MERENJA PROTOKA NA SPOJU KOLEKTORA SA SILOVITIM TEČENJEM

HYDRAULIC MODEL STUDY OF TURBULENT FLOW MEASUREMENT IN SEWER PIPES CONJUNCTION

REZIME

U radu su prezentovane mogućnosti i prednosti primene modelskih ispitivanja u analizi tečenja u velikim kanalizacionim kolektorima opšteg sistema kanalisanja. Na primeru objekata koji funkcionišu u sastavu beogradskog kanalizacionog sistema, prikazano je kako se na modelu, sa velikim stepenom pouzdanosti mogu izučavati karakteristike toka u kanalizacionim kolektorima i njihovim spojevima. Posebno je istaknuta uloga modelskih ispitivanja prostornih tečenja u objektima složene geometrije. Takođe, model je predstavljen i kao veoma pouzdano i očigledno sredstvo za davanje predloga o položaju budućih mernih mesta u beogradskoj kanalizaciji.

Ključne reči: hidraulički fizički modeli, kanalizacioni kolektori, opšti sistem kanalisanja.

SUMMARY

This paper presents capabilities and benefits of use of physical models for flow analysis in large sewer pipes and conjoining objects. A group of objects pertaining to the Belgrade Sewer System is modelled and results are briefly discussed. The results show that the study of flow characteristics in sewer pipes and conjoining objects on the model can be done with a high level of confidence. Special attention has been drawn to the role of physical models in 3-dimensional flow investigation in nonstandard and objects of great complexity. Also, a physical model is introduced as a reliable and straightforward tool in decision making in positioning of future measuring points in Belgrade Sewer System.

Key words: scale model, sewer pipes, combined sewer system.

1. UVOD

Izgradnja objekata komunalne hidrotehnike u urbanim gradskim jezgrima predstavlja sve veći građevinski izazov. I pored savremene opreme i usavršenih tehnologija gradnje postojeći objekti i instalacije pod zemljom stvaraju komplikovane uslove za izgradnju novih infrastruktura, pa trase kolektora i položaji njihovih spojeva često bivaju iznuđeni, uslovno rečeno. Uslovima izgradnje nametnuta geometrija, uglavnom ne ide u prilog korektnom hidrauličkom funkcionisanju ovih objekata. Komplikovani oblici stvaraju složeno prostorno tečenje koje je veoma teško predvideti i proračunavati standardnim procedurama u toku projektovanja.

Sa stanovišta hidrauličkog funkcionisanja, neprilike mogu izazvati previše blagi (ili čak kontra) padovi, jako strmi padovi, trase kolektora sa naglim skretanjima, ili spojevi kolektora izvedeni pod uglom koji nepovoljno utiču na transportnu moć, odnosno propusnost objekta.

1. INTRODUCTION

Construction of urban hydraulic objects is a growing construction challenge. Despite the modern equipment and improved technology of building the existing underground objects and installations create complicated building conditions for new infrastructure – positioning of pipelines and their joints is imposed. These conditions are usually in discordance with proper hydraulical performance (functioning) of the system. Complex shapes create complicated spatial flow which is rather difficult to predict and calculate with standard design procedures.

From the standpoint of hydraulic performance, troubles can be caused by mild (or even counter) slopes, very steep slopes, sewer pipes with sudden turns, or conjunctions designed with an angle that reduces transport capacity of the object.

Physical models are very successful in solving these problems. These are scaled replicas of real objects, designed to follow the same physical laws of similitudes – in this way the model can be used as an ex-

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U rešavanju ovakvih problema, godinama unazad veoma se uspešno koriste fizički modeli. To su modeli objekata u prirodi, izrađeni u odgovarajućoj razmeri, a projektovani po fizičkim zakonima sličnosti koji omogućavaju da se hidrauličke karakteristike toka u prirodi sa velikim stepenom pouzdanosti predvide na osnovu analize tečenja na modelu. Ovim pristupom smanjuje se rizik u projektovanju složenih hidrotehničkih objekata što utiče na njihovu funkcionalnost, bezbednost ostalih infrastuktura, smanjenje troškova održavanja i eksploatacije ovih objekata itd.

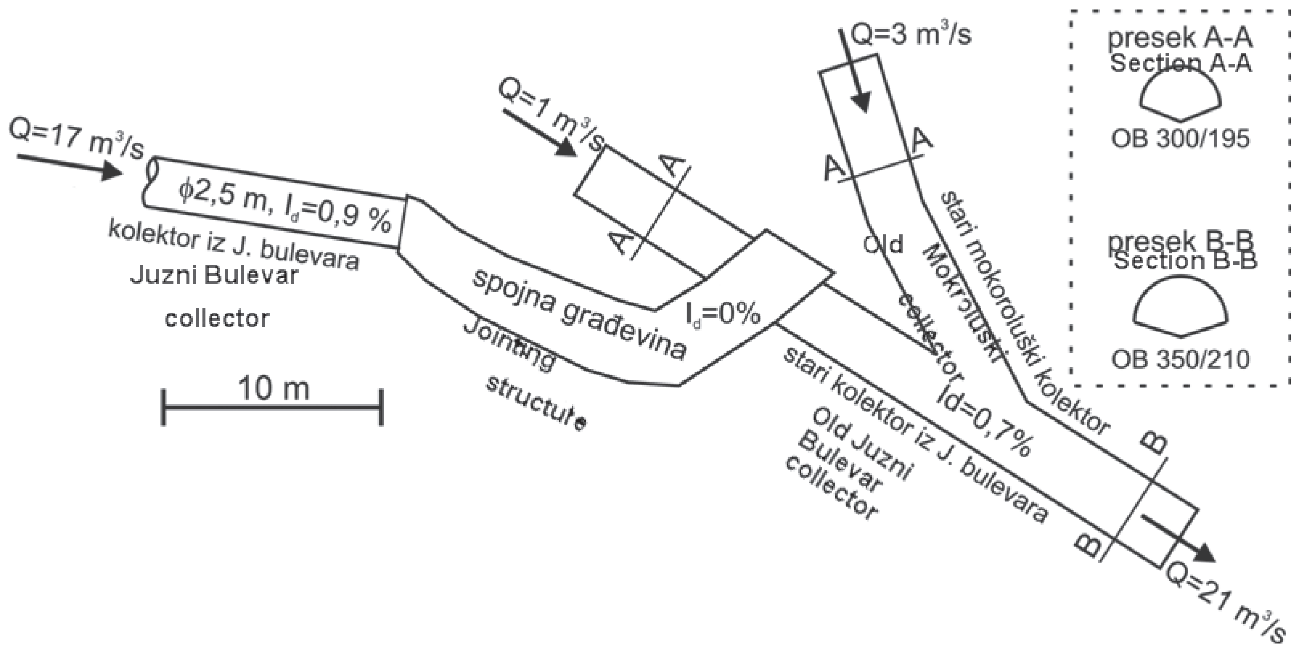
2. OPIS MODELA

Detaljnom rekonstrukcijom Južnog bulevara u Beogradu, izvršena je zamena svih podzemnih instalacija. Glavni kanalizacioni vod, takođe je rekonstruisan, postavljanjem korugovanog polietilenskog kolektora, kružnog poprečnog preseka, prečnika 2,5 m. Ranije projektovana trasa nije mogla da bude realizovana zbog položaja vijadukta na Autokomandi. U Bokeljskoj ulici, ispod površine terena, projektovana je i izvedena armiranobetonska građevina, slika 1., čija je uloga uvođenje otpadne vode iz ovog kolektora u Stari mokroluški kolektor. Iznad trase Starog mokroluškog kolektora nalazi se deo pomenutog vijadukta. Usled zahteva za bezbednom udaljenošću od stubova nadvožnjaka, izvedena je građevina prilično nestandardnog oblika, koja se spaja u Stari mokroluški kolektor pod nepovoljnim uglom. Objekat u osnovi ima jedan nagli prelom neposredno pre spoja sa Sm kolektorom, slika 2., preseci C i D. Računski protok kolektora u Južnom bulevaru iznosi 17,7 m^3/s,

cellent tool to predict flow characteristics in the real object by analyzing the flow on the model, with a great degree of reliability. This approach reduces risks that exist in design of complicated hydrotechnical objects, increasing their functionality, performance, giving additional protection to surrounding infrastructure, lessening operation and maintenance costs, etc.

2. MODEL DESCRIPTION

Detailed reconstruction of the Juzni Bulevar Street in Belgrade included the replacement of all underground installations. The main sewer line was also reconstructed by placing corrugated polyethylene pipes, with circular cross-section with diameter of 2,5 m. It was impossible for the pipe to follow its design trajectory due to the position of viaducts Autokomanda. In Bokeljska Street, a reinforced concrete underground structure was designed and built, Figure 1. Its role is to import used waters from Juzni Bulevar collector to the Old Mokroluski collector. Above the route of the Old Mokroluski collector is a part of the mentioned viaduct. Due to demands for a safe distance from the pillars of the bridge, design of the joining structure is with rather non standard shapes and it connects with the Old Mokroluski collector under unfavorable angle. The building basically has a sudden break just before the junction with the OM collector, Figure 2, sections C and D. Projected flow of the collector in the Juzni Bulevar Street is 17.7 m^3 / s, which combined with a steep longitudinal slope of circa 0.9% creates all the necessary conditions for supercritical flow, with veloci-



Slika 1. Situacija – položaj kanalizacionih kolektora i njihovi spojevi
Figure 1. The situation - the position of sewer collectors and their conjunctions

što uz relativno veliki uzdužni pad od oko 0,9% stvara uslove za izrazito burno tečenje sa brzinama koje dostižu i 6 m/s. Jasno je da se postavilo pitanje o mogućnostima bezbednog uvođenja ovako velike količine vode sa značajnom kinetičkom energijom u kolektore izrađene od nearmiranog betona pre više decenija.

Projektovano je i izvedeno suženje u zoni preloma građevine u osnovi, u nastojanju da se postigne, povoljniji ugao pod kojim će tok vode ući u Stari mokroluški kolektor, slika 2. Izdizanjem nivoa u građevini dolazi do uspostavljanja mirnog tečenja, čime se omogućava lakše skretanje toka vode nego u burnom režimu. Istovremeno na prelazu iz burnog u miran režim tečenja obrazuje se hidraulički skok u kom se deo kinetičke energije (značajne razorne moći) utroši. U suženju koje omogućava nesmetan transport nanosa po dnu, ostvaruje se kritična dubina (otprilike u preseku 8, slika 2.). Poznato je da tok, na profilu na kom se ostvaruje kritična dubina poseduje minimum specifične energije, pa je veza između protoka i kritične dubine na tom mestu jednoznačna. Ova osobenost se koristi u praksi merenja protoka – ukoliko odredimo kritičnu dubinu, za poznatu geometriju dobijamo protok, pod pretpostavkom da je Frudov broj jednak jedinici. Međutim, kako je merenje kritične dubine uglavnom teško zbog nemirnog vodnog ogledala i nepoznavanja tačnog položaja preseka na kome se javlja, jednostavnije je meriti dubinu neposredno uzvodno od suženja u preseku u kome je uspostavljeno mirno tečenje. Veza između ove, uzvodne dubine i protoka je takođe jednoznačna.

Kako bi se složeno prostorno tečenje unutar objekta što bolje sagledalo i na taj način otklonile posledice eventualnih propusta projekta, došlo se do odluke o izradi hidrauličkog fizičkog modela. U laboratoriji Instituta za hidrotehniku i vodno-ekološko inženjerstvo Građevinskog fakulteta Univerziteta u Beogradu, u razmeri za dužine 1:10 napravljen je model spoja pomenutih kolektora, prikazanih na slici 1. Model je projektovan po Frudovoj sličnosti. Na uzvodnim delovima modela kolektora postavljeni su rezervoari sa umirivačima i ustavama kako bi se korektno definisali uzvodini granični uslovi sa silovitim tečenjem. Protok se na modelu reguliše i meri preko Tomsonovih preliva.

3.0. REZULTATI MERENJA NA MODELU

Na modelu su izvršena merenja za nekoliko različitih scenarija, koji odgovaraju protocima od: 1, 2, 5, 10 i 12 m^3/s u prirodnim uslovima. U svim mernim profilima, prikazanim na slici 2., mereni su nivoi vode pri različitim protocima. Kako tečenje ima izražen prostorni karakter, nivo slobodne površine duž jednog profila nije ni približno horizontalan, pa su na svakom pojedinom profilu, nivoi mereni uz levi i desni zid građevine. Na osnovu tih merenja, određene su

ties exceeding 6 m / s. It is clear that there is a great concern related to import of this large amount of water, with significant kinetic energy, into the rather old collector made of non-reinforced concrete.

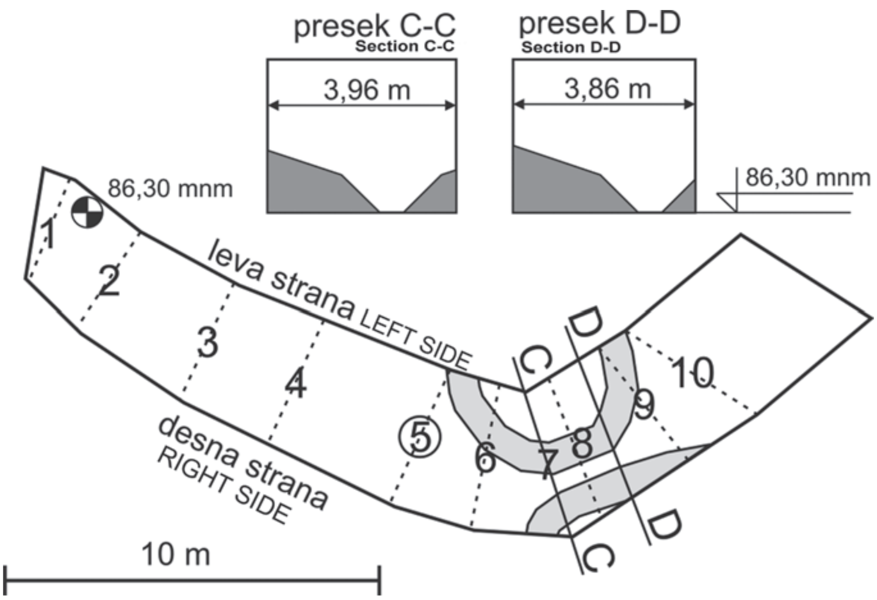
A contraction was designed and constructed in the zone of the sudden turn, in order to achieve a suitable angle for water inflow into the Old Mokroluski collector, Figure 2. The contraction causes elevation of the water level in the upstream part of the structure making the flow subcritical, allowing easier turning (than when the contraction does not exist and the flow is supercritical). At the same time the transition from supercritical to subcritical flow regime forms a hydraulic jump, which represents and efficient mechanism for energy dissipation. The contraction is designed in a way that allows uninterfered sediment transport and formation of critical depth (approximately in the section 8, Figure 2). It is known that flow, in the profile which achieves the critical depth has a minimum of specific energy, and the relation between flow and critical depth is unequivocal in that place. This characteristic is used in the practice of flow measuring - if we determine the critical depth for a known geometry we get the flow, assuming that the Froude number is one. However, as the measurement of critical depth is generally difficult due to restless water table and not-known exact position of the profile where it exists, it is easier to measure the depth just upstream from the narrowing (where the flow regime is subcritical) The relation between the upstream depth and flow is also unequivocal.

A scale model of the conjoining structure with inflow and outflow pipes was made to analyze spatially complex flow inside the object and to eliminate the consequences of any failure of the project, a scale model should be made. In the laboratory of the Institute for Hydrotechnics and Environmental Engineering at the Faculty of Civil Engineering, University of Belgrade, in the ratio for length of 1:10, a model of conjoined collectors was made, shown in Figure 1. The model was designed in accordance with Froude similitude. The upstream parts of the model collectors are reservoirs with gates which assure correct definition of upstream limits for supercritical flow. The flow in the model is regulated and measured by Thomson's weir (V-notch sharp-crested weir).

3.0. RESULTS OF THE MODEL MEASUREMENTS

Measurements on the model were made for several different scenarios, which correspond to flows of 1, 2, 5, 10 and 12 m^3/s in natural conditions. In all measurement profiles, shown in Figure 2, water levels were measured at different water discharges. As flow has a strongly spatial character, the level of the free surface along a profile is not nearly horizontal, and on each individual profile,

profil section	leva stacion. [m] left stationary [m]	desna stacion. [m] right stationary [m]
1	0.7	0.1
2	3.0	1.9
3	5.8	5.2
4	8.3	7.7
5	11.9	11.3
6	13.3	13.5
7	13.9	16.1
8	14.3	17.9
9	16.2	19.8
10	17.0	21.9



Slika 2. Dispozicija spojne građevine sa položajem suženja i mernih profila
Figure 2. Disposition of jointing structures with contraction and measuring profiles

linije nivoa, dijagrami na slici 3. i slici 4. Dijagrami prikazani na slici 3. predstavljaju linije nivoa merene uz desni zid građevine pri nekoliko protoka. Za različite protoke ove linije nivoa imaju dosta slične oblike. Uočava se, da između stacionaža 10 i 16 m (koje odgovaraju profilima 5 i 7), linija nivoa raste, i to je posledica potopljenog skoka sa prostornim karakterom. Kritična dubina ostvaruje se otprilike u preseku 8, na stacionaži 18 m. U objektu je ostvareno mirno tečenje sa graničnim vrednostima Frudovog broja.

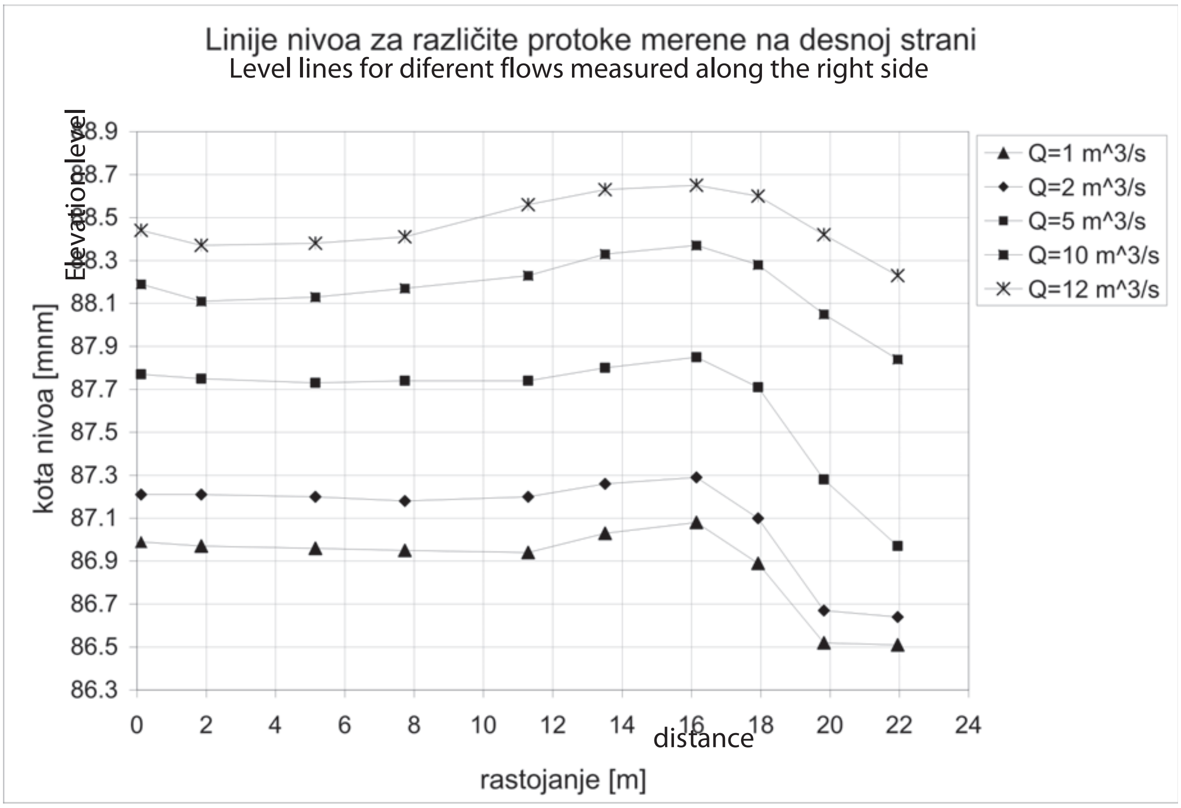
Dijagramima na slici 4., predstavljene su, linije nivoa merene uz levi zid građevine. Dijagrami ukazuju na povećanje nivoa na početnim stacionažama, što je posledica naleta mlaza, koji velikom brzinom ističe iz kolektora iz Južnog bulevara na levi zid građevine, u zoni preseka 1 i 2. Na modelu su ove pojave i vizuelno uočljive.

Modelska istraživanja mogu se koristiti i u svrhe određivanja hidraulički najpovoljnijih lokacija za postavljanje opreme za merenje i monitoring na objektima. Na osnovu prikupljenih podataka, razmotrena je već pomenuta mogućnost uspostavljanja jednoznačne veze između protoka i nivoa u određenom preseku. Preliminarnom, vizuelnom ocenom tečenja, presek 5 se izdvaja kao presek sa relativno najmirnijim nivoom slobodne površine. Ovaj presek se nalazi neposredno uzvodno od suženja. Tražena je zavisnost između kote nivoa u ovom preseku i poznatog (kontrolisanog) protoka kroz instalaciju. Na slici 5. prikazane su krive protoka na profilu 5. Nivo je meren, kao što je već objašnjeno, sa obe strane profila. Dobijene su glatke krive, na kojima se jasno uočava jednoznačnost veze protoka i kote nivoa. To ukazuje

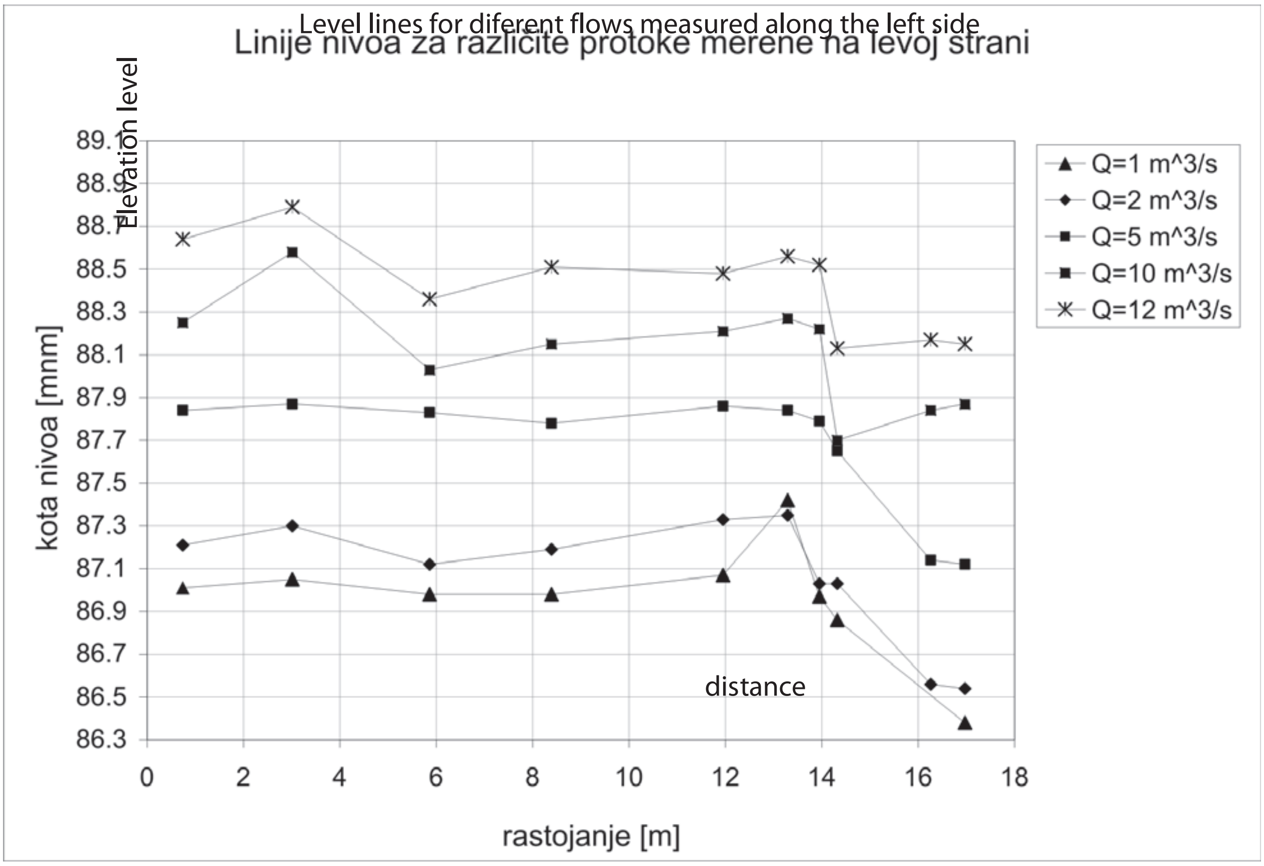
the levels were measured near the left and the right wall of the building. Level lines are determined on the basis of these measurements, diagrams in Figure 3 and 4. Diagrams shown in Figure 3 represent the level lines measured along the right wall of the building. For different discharges, level lines have quite similar shapes. It is obvious, that between the stationary 10 and 16 m (corresponding to sections 5 and 7), line level increases, and this is the result of a complex (3D) hydraulical jump that is formed. Critical depth is achieved near section 8, at the stationary 18 m. Subcritical flow is achieved in the object with the limit values of Froude number.

Diagrams in Figure 4, represent the level lines measured by the left wall of the building. Diagrams show the elevation of water level in the upstream part of the object, which happens as a consequence of high-velocity flow from the Juzni Bulevar collector entering the object with an unfavorable angle and "hitting" the wall of the building in the zone of sections 1 and 2.

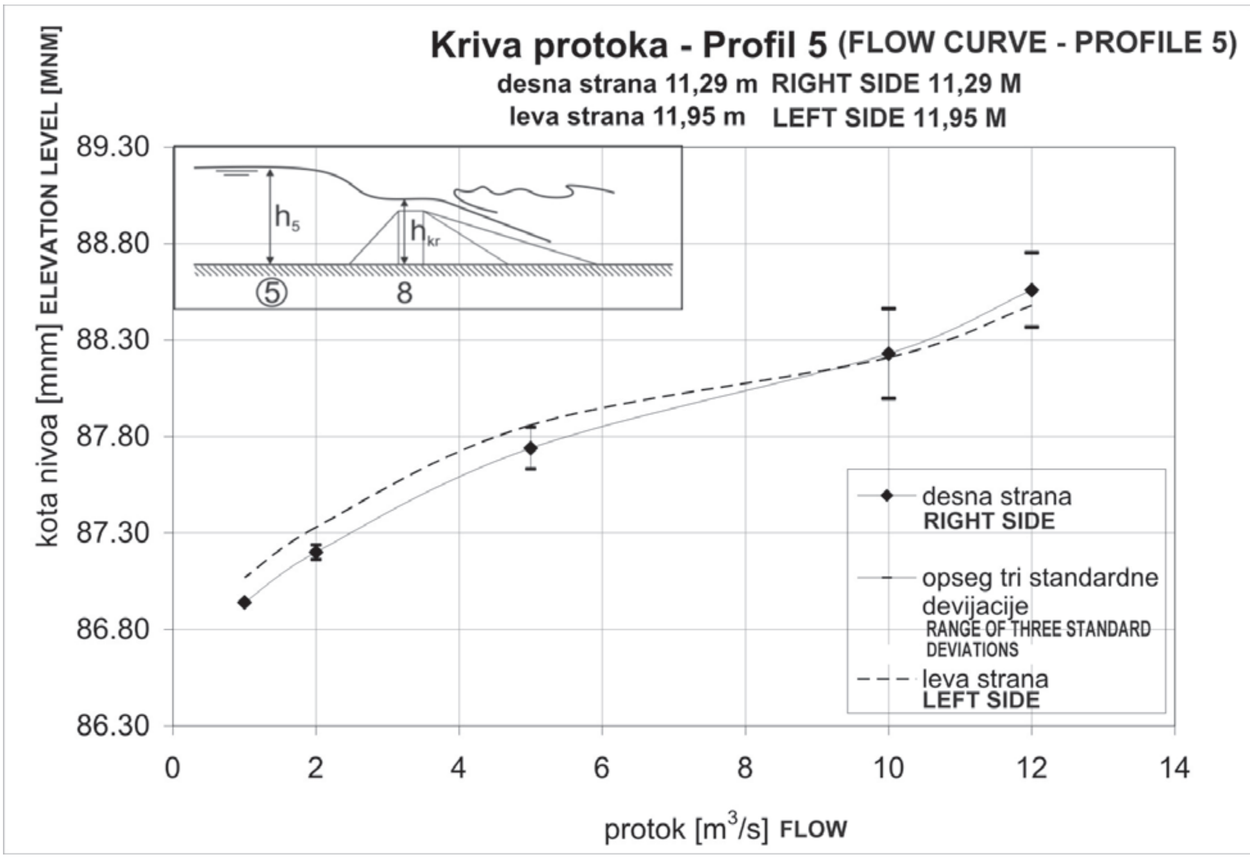
Research model can be used in purposes of determining the most desirable hydraulic locations for setting up the equipment for measuring and monitoring facilities. On the basis of collected data, mentioned possibility of establishing a unique relation between flow and levels in a particular intersection is already discussed. By preliminary, visual estimation, section 5 is identified as a cross-section with relatively calm level of the free surface. This section is located immediately upstream from the contraction. Analysis was done to investigate whether there is a relationship between the elevation level at this section and flow through the installation. Figure 5 shows the flow curves (water level vs. flow diagrams) in the profile 5. The level was measured, as alre-



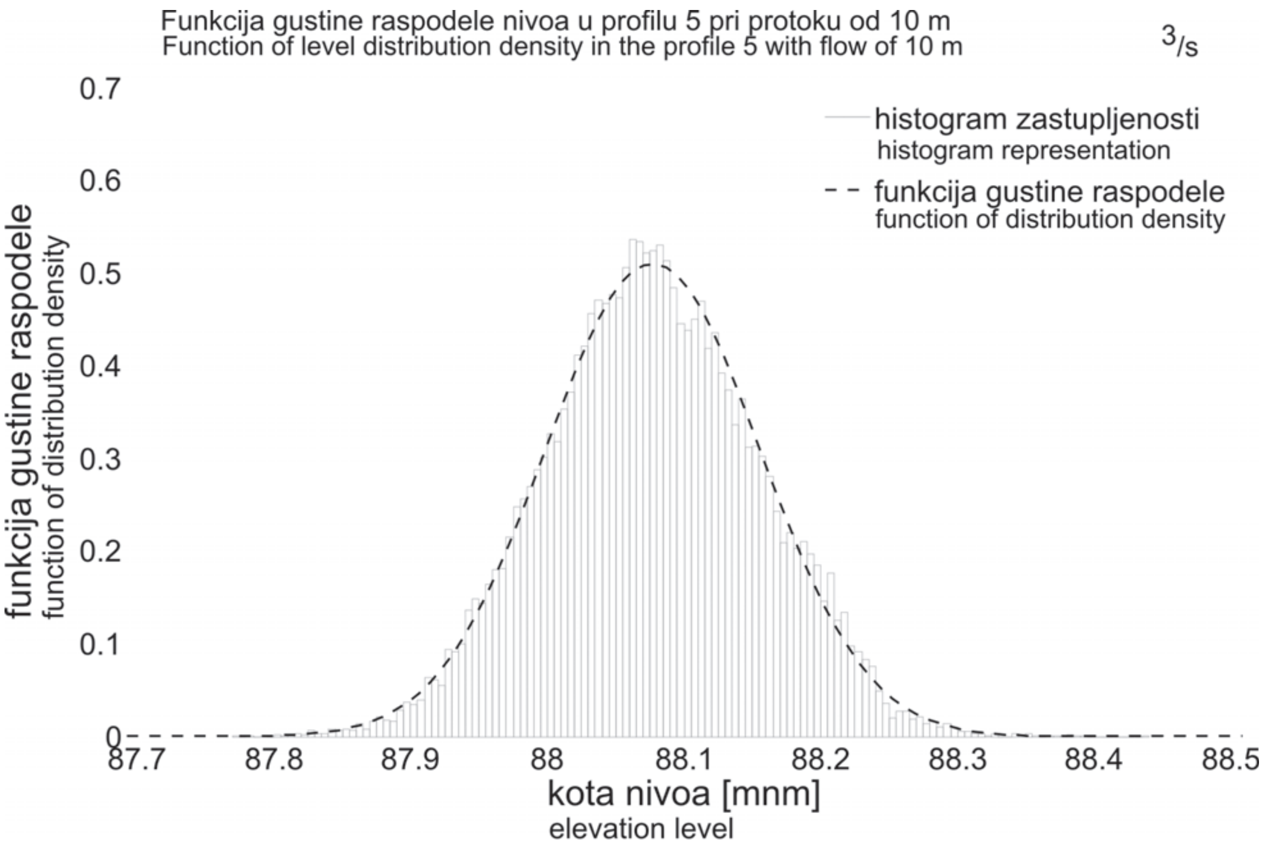
Slika 3. Linije nivoa merene uz desni zid građevine
Figure 3. Level lines measured along the right wall of the building



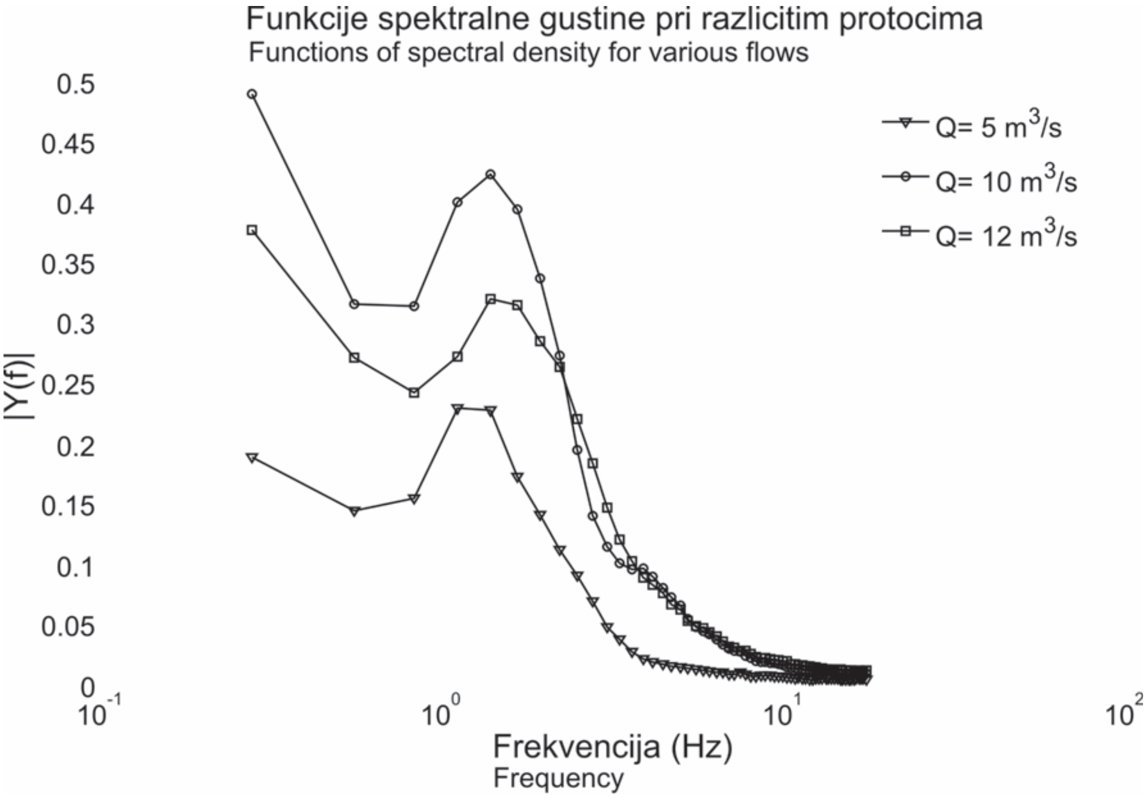
Slika 4. Linije nivoa merene uz levi zid građevine
Figure 4. Level lines measured along the left wall of the building



Slika 5. Zavisnot protoka i kote nivoa u profilu 5
Figure 5. Dependence between flow and elevation level in the profile 5



Slika 6. Kote nivoa u profilu 5 prate normalnu raspodelu
Figure 6. Elevation levels in profile 5 follow the normal distribution



Slika 7. Funkcije spektalnih gustina kote nivoa u preseku 5
Figure 7. Functions of spectral density of elevation levels in profile 5

na činjenicu da je merni profil korektno odabran. Pošto nivo u profilu 5 nije potpuno miran, da bi se odredio karakter oscilovanja nivoa u vertikalnom pravcu, pored merenja sa standardnim mernim iglama, mereno je i kapacitivnom sondom. Obradom signala sa kapacitivne sonde došlo se do podataka o veličini odstupanja nivoa u ovom profilu od neke srednje vrednosti i frekvenciji tih odstupanja. Na slici 5., na krivoj protoka dobijenoj merenjem nivoa uz desni zid građevine, prikazan je i opseg nivoa od tri standardne devijacije, pošto je ustanovljeno da nivoi u jednom preseku slede normalnu raspodelu, a to je prikazano na slici 6. Na primer, za protok od 10 m^3/s (slika 5.) jasno se uočava da greška u merenju kote nivoa na profilu 5, značajno utiče na grešku u određivanju protoka (7,8 do 11,5 m^3/s). Zbog toga je preporuka da se iskoristi merna i akviziciona oprema sa vremenskim osrednjavanjem nivoa, pa da se na osnovu osrednjene vrednosti na objektu sračuna protok, preko kalibracione krive dobijene na modelu.

Na slici 7., prikazani su dijagrami spektralne gustine nivoa u profilu 5. Ove krive ukazuju da postoji privilegovana frekvencija od oko 1,5 Hz kojom nivoi osciluju u datom preseku, za sva tri prikazana protoka od 5, 10 i 12 m^3/s. Ono što se takođe uočava jeste da su amplitude tih oscilacija najveće za protok od 10 m^3/s. Ovo se može objasniti činjenicom da za veće protoke dolazi do intenzivnijeg potapanja hidrauličkog skoka, koji se javlja na ulazu u građevinu i do relativnog smirivanja oscilacija nivoa po amplitudi.

ady explained, on both sides of the profile. Smooth curves are obtained, which clearly represents the unique connection between flow and elevation levels. This points out to the correctly selected measuring profile. Since the level in the profile 5 is not completely calm, to determine the character of the oscillation level in the vertical direction, in addition to measuring with standard measuring needles, measurement was also done with capacity probe. Processing of the capacity probe signal led to the data on the size of the deviation level in this profile including arithmetic mean and frequency of these deviations. Figure 5, on the flow curve obtained by measuring the levels along the right wall of the building, shows a range of levels of three standard deviations, since it was found that levels in one section follow normal distribution, and this is shown in Figure 6. For example, for the flow of 10 m3/s (Fig. 5) it is clearly recognizable that the error in measuring elevation level in profile 5, significantly affect the error in determining the flow (7.8 to 11.5 m3 / s). Therefore, it is recommended to use measuring and acquisition equipment with time averaging level, and to calculate flow on the basis of average value, using the calibration curves obtained in the model.

In Figure 7, are shown diagrams of spectral level density in the profile 5. These curves indicate that there is a privileged frequency of about 1.5 Hz for each oscillating level in observed section, for all three flows of 5, 10 and 12 m^3/s. Also it can be observed that the amplitudes of these oscillations are at their maximum for the flow of 10 m^3/s. This can be explained by the fact that for hig-

Hidraulički model nudi i mogućnost merenja opterećenja od vode na konstrukciju. Mogu se meriti pritisci, a zatim potražiti sile usled njhove srednje vrednosti i fluktuacione komponente. Ova merenja su u toku i biće sigurno prezentovana na jednoj od narednih tematskih konferencija.

4. ZAKLJUČAK

Modelska ispitivanja hidrotehničkih konstrukcija, a posebno onih nestandardnih, nameću se kao najpouzdaniji, a relativno ekonomičan pristup u analizi složenih prostornih tečenja unutar kontura ovih objekata. Ovakva istraživanja, u procesu projektovanja, najčešće unapred bivaju diskreditovana argumentima o manjku vremena i nedostatku novčanih sredstava da se izvedu, iako se zna da procentualno čine srazmerno mali deo ukupnih troškova projekta. Nasuprot njima su složeni numerički modeli, čiji rezultati imaju veliki stepen neizvesnosti usled nedovoljnog poznavanja konturnih i unutrašnjih graničnih uslova, koji onemogućavaju njihovu kalibraciju i verifikaciju bez prethodnih merenja na terenu, ili na fizičkom modelu.

Izgradnja postrojenja za tretman otpadnih voda, zahteva da se podsistemi kanalizacionog sistema, od kojih neki funkcionišu kao potpuno nezavisne celine, integrišu u veći funkcionalni sistem kako bi otpadne vode sa teritorije celog grada dospele na jedno ili vrlo mali broj postrojenja. Javiće se dakle potreba za izgradnjom novih kolektora i objekata koji ih spajaju sa postojećim infrastrukturama. Funkcionalnost svakog ovog objekta uticaće na opštu funkcionalnost i bezbednost kanalizacionog sistema. Zbog toga bi rad svih, ili većine, ovih objekata trebalo preliminarno proveriti na fizičkim modelima.

her flows the hydraulic jump at the object's entrance loses it intensity as it becomes covered with more water, and level oscillation diminishes.

Hydraulic model offers the possibility of measuring the load of water on the structure. Pressures, forces resulting from their average value and fluctuation components can also be obtained by this model.

4. CONCLUSION

Model testing of hydraulic structures, especially those non-standard, are imposed as a reliable and relatively cost-effective approach to the analysis of complex spatial flow within the contours of these objects. Such researches, in the process of design, are often discredited by arguments about the lack of time and lack of money, although it is known that they make relatively small percentage of the total project cost. On the contrary there are complex numerical models, whose results have a large degree of uncertainty due to insufficient knowledge of contour and internal limiting conditions, which prevent their calibration and verification without previous measurements in the field, or on the scale model.

Construction of facilities for wastewater treatment requires that the sewer subsystems, of which some operate as fully independent units, should be integrated into larger functional system in order to drainage waste water from the territory of the entire city to one or a very small number of plants. So there will be a need for new collectors and objects that connects them with existing infrastructures. The functionality of each object will affect the overall functionality and security of the sewerage system. Because of that, the work of all, or most of these facilities should be preliminary investigated on physical models.

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