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MATEMATIČNO MODELIRANJE TOKA SOČE NA OBMOČJU IZTOKA HIDROELEKTRARNE PLAVE II
MATHEMATICAL MODELLING OF THE SOČA RIVER FLOW IN THE AREA OF THE PLAVE II POWER PLANT OUTFLOW

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Pri turbinskem iztoku hidroelektrarne (HE) Plave II se struga Soče nekoliko razširi, zato na tem območju obstaja nevarnost zasipavanja s prodom. S primerno oblikovanim talnim pragom tik gorvodno od iztoka je treba pri prodonosnih pretokih tok reke Soče preusmeriti tako, da povečane hitrosti ob desnem bregu izpirajo prod in preprečujejo recirkulacijo. Dvodimenzijski hidravlični izračun je obravnaval odsek Soče v dolžini približno 800 m. Za umerjanje modela smo uporabili enodimenzijske račune in podatke o gladinah visokih voda za stanje med gradnjo, ko je bila gradbena jama strojnice HE Plave II zaščitena z začasnim visokovodnim nasipom. Razmere pred izgradnjo nasipa pa so nam služile kot referenca za primerjavo s končnim stanjem po odstranitvi pomožne pregrade in izgradnji prodnega praga. Pri nižjih pretokih Soče (Q = 100, 200 in 300 m^3/s) je bilo raziskanih več različic oblike praga. Za končno predlagano rešitev pa je značilna lomljena oblika v tlorisu, zniževanje krone praga proti desni brežini in hidravlično ugodno oblikovana priključitev praga na desno brežino. Preverili smo bile tudi hidravlične razmere pri visokih vodah. Pri stoletnem pretoku Q_{100} = 2718 m^3/s potek gladin na območju hiš na levem bregu gorvodno od pragu kaže, da talni prag tudi v primeru zaproditve do krone razmer, v primerjavi s stanjem pred začetkom izgradnje strojnice HE Plave II, ne poslabšuje zaznavno.
Ključne besede: *dvodimenzijsko hidrodinamično modeliranje, model PCFLOW2D, Soča, iztok HE Plave II, talni prag, prodonosnost, sedimentacija*

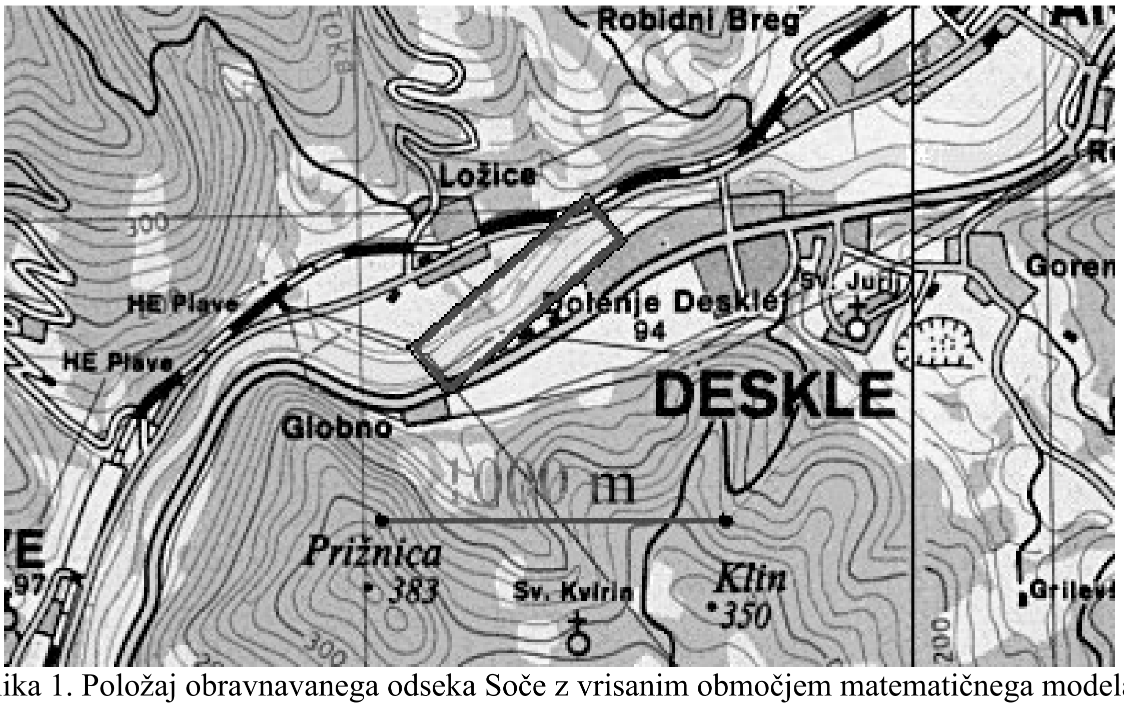
Due to the widening of the Soča riverbed near the Hydro Power Plant Plave II outflow, there is a possibility of sedimentation. It is necessary to build a bottom sill just upstream of the outflow in order to redirect the flow of the Soča River in the way that increased velocities near the right bank could flush bed-load and prevent recirculation. A two-dimensional hydraulic computation was applied on the 800 m long Soča River reach. The results of one-dimensional computations and measured water elevations near the temporarily-built flood levee in the vicinity of the HPP Plave II power house were used for the model calibration. At lower discharges of the Soča River (Q = 100, 200 and 300 m^3/s), several variants of the proposed bottom sill were investigated. As a final solution, a "broken-line" weir with a lowered crest near the right bank and a hydraulically optimized connection to the bank were suggested. In addition, the high water stages were also investigated. Even when the available sedimentation volume is fully filled with sediment to the weir crest elevation, the water surface elevations near the houses at the left bank just upstream of the weir were not significantly higher at the flood discharge of Q_{100} = 2718 m^3/s.
Key words: *twodimensional hydrodynamic modelling, PCFLOW2D code, the Soča River, HPP Plave II outflow, bottom sill, bed load transport, sedimentation*

1. UVOD

Pri projektiranju iztoka iz hidroelektrarne (HE) Plave II je bilo treba upoštevati veliko prodonosnost reke Soče. Območje iztoka (slika 1) bi bilo lahko ogroženo z odlaganjem plavin, ki jih s seboj nosi reka, kar bi negativno vplivalo na delovanje hidroelektrarne. Zaradi dviga dna struge bi se dvignila tudi gladina spodnje vode, kar bi povzročilo zmanjšanje moči hidroelektatrne, v ekstremnih primerih pa bi lahko prišlo tudi do nezaželenega zasipavanja iztoka. Zato je bil med zoženim delom struge reke Soče dolvodno od mostu v Desklah in iztokom iz HE Plave II v letu 2001 zgrajen kamnito-betonski prag, ki ima dvojni namen. Z ustrezno izbrano koto krone preliva se je za pragom ustvaril prodni zadrževalnik, ki pri visokih vodah vsaj delno ustavi transportirani material. Pri določanju kote krone praga je bilo treba upoštevati gorvodni dvig gladine vode, ki bi lahko poplavila stanovanjske objekte na levem bregu Soče v Desklah. Druga vloga praga pa je, da pri obratovalnih pretokih usmerja tok proti iztoku iz HE, kjer povečane hitrosti vodnega toka preprečujejo odlaganje rinjenih plavin.

1. INTRODUCTION

At the design process of the outflow from the Plave II hydro power plant (HPP) it was necessary to take into account the large bed-load transport capacity of the Soča River. The area of the Soča River near the outflow (Figure 1) could be affected by sedimentation and the power plant operation could become less effective. The rise of the river bottom would increase the tailwater surface elevations. As a consequence, the HPP power capacity would be reduced or the plant operation completely stopped by the sedimentation of the outflow. To prevent such a situation, a concrete bottom-sill was built in 2001 in the Soča riverbed just upstream of the HPP Plave II outflow. The first aim of the sill was to form a sediment retention upstream, where bed-load material could be partly trapped at flood discharges. The bottom-sill crest elevations were determined by taking into account the backwater effect, which could cause floods at the houses on the left bank of the Soča River near the village of Deskle. The second aim of the bottom-sill was to redirect the flow of the Soča River towards the HPP outflow, where bed-load deposition should be prevented by increased flow velocities.



Slika 1. Položaj obravnavanega odseka Soče z vrisanim območjem matematičnega modela.
Figure 1. Layout of the Soča River reach with the area of the mathematical model.

Za reševanje podobnih problemov se v hidrotehnični praksi običajno uporabljajo enodimenzijski matematični modeli. Zaradi značilne oblikovanosti struge reke Soče na obravnavanem območju ter zaradi izbranega položaja in oblike praga so bile pričakovane znatne spremembe gladine tudi v prečni smeri. Nastal je poudarjeno neenakomeren tok z izrazito večjimi hitrostmi ob desni brežini. Z enodimenzijskimi modeli takšnih neenakomernih razporeditev hitrosti po prečnem preseku ne bi bilo mogoče ustrezno ponazoriti.

Zato je bil za simulacijo toka reke Soče čez prag in ob iztoku iz HE Plave II izbran dvodimenzijski hidrodinamični matematični model PCFLOW2D. S tem modelom lahko napovemo potek gladine tudi v prečni smeri in izračunamo globinsko povprečne hitrosti toka v vodoravni ravnini. S pomočjo analize tokovnih razmer tako pri obratovalnih kot tudi pri visokovodnih pretokih je bil ob sodelovanju projektantov (Fazarinc, 2001; IBE, 1997) določen položaj, oblika in višinski položaj praga.

Podrobna simulacija toka nad samim pragom bi sicer zlasti pri nizkih pretokih zahtevala uporabo zahtevnejšega tridimenzionalnega modela. Vendar nas je v okviru opisane študije zanimalo predvsem globinsko povprečno hitrostno polje tik dolvodno od praga in vpliv na gladine gorvodno, zato je bil izbran dvodimenzijski model PCFLOW2D, ki je bil že uspešno uporabljen za simulacijo podobnega primera toka preko talnih pragov v kajakaški progi v Tacnu (Četina & Rajar, 1993).

To solve similar problems in hydraulic engineering, one-dimensional mathematical models are usually used. Due to the specific Soča riverbed configuration and the chosen layout and shape of the bottom-sill, significant changes of the water surface elevations were expected in the lateral direction, too. A pronounced non-uniform flow with higher velocities near the right bank occurred. One-dimensional models would not be able to simulate such non-uniform velocity distributions in river cross sections in an appropriate way.

The two-dimensional PCFLOW2D mathematical model was chosen to simulate the Soča River flow over the bottom sill near the Plave II HPP outflow. The model could predict changes of water surface elevations in longitudinal and lateral directions, and calculate the depth-averaged velocity field. The detailed analysis of the flow at operational and flood discharges helped the designers (Fazarinc, 2001; IBE, 1997) to determine the final layout, shape and crest elevations of the bottom-sill.

At low discharges, a more sophisticated three-dimensional model would be needed to simulate flow details over the bottom sill. But since the main purpose of the study was to simulate the depth-averaged velocity field downstream of the sill and a backwater effect upstream, the two-dimensional model PCFLOW2D was chosen. It has already been successfully used for the study of similar flow over the bottom weirs in the Tacen kayak racing channel (Četina & Rajar, 1993).

2. MATEMATIČNI MODEL

2.1 OSNOVNE ENAČBE

V dvodimenzijskem matematičnem modelu PCFLOW2D so bile za obravnavani primer reke Soče upoštevane kontinuitetna (1) in dinamični enačbi v x in y smeri (enačbi (2) in (3)) za stalni globinsko povprečni tok. Koeficient efektivne viskoznosti υ_{ef} določimo

2. MATHEMATICAL MODEL

2.1 BASIC EQUATIONS

For the case of the Soča River flow in the PCFLOW2D two-dimensional mathematical model, the continuity (1) and dynamic equations in the x and y directions (equations (2) and (3)) for steady depth-averaged flow were used. The coefficient of effective s pomočjo enačbe (6) in dveh dodatnih transportnih enačb (4) in (5) za k in ε, kar je znano kot t. im. globinsko povprečna verzija k-ε modela turbulence (Rodi, 1980). Podroben opis enačb in pomen posameznih členov v njih je možno najti v literaturi (npr. Četina, 1989; Četina & Rajar, 1993).

turbulent viscosity υ_{ef} was determined by equation (6), and the two additional transport equations (4) and (5) for k and ε which are known as the depth-averaged versions of the k-ε turbulence model (Rodi, 1980). A more detailed description of the equations and individual terms can be found in the literature (e.g. Četina, 1989; Četina & Rajar, 1993).

$$\frac{\partial(hu)}{\partial x}+\frac{\partial(hv)}{\partial y}=0 \qquad (1)$$

$$\frac{(hu^2)}{\partial x}+\frac{\partial(huv)}{\partial y}=-gh\frac{\partial h}{\partial x}-gh\frac{\partial z_b}{\partial x}-ghn^2\frac{u\sqrt{u^2+v^2}}{h^{4/3}}+\frac{\partial}{\partial x}(h\upsilon_{ef}\frac{\partial u}{\partial x})+\frac{\partial}{\partial y}(h\upsilon_{ef}\frac{\partial u}{\partial y}) \qquad (2)$$

$$\frac{(huv)}{\partial x}+\frac{\partial(hv^2)}{\partial y}=-gh\frac{\partial h}{\partial y}-gh\frac{\partial z_b}{\partial y}-ghn^2\frac{v\sqrt{u^2+v^2}}{h^{4/3}}+\frac{\partial}{\partial x}(h\upsilon_{ef}\frac{\partial v}{\partial x})+\frac{\partial}{\partial y}(h\upsilon_{ef}\frac{\partial v}{\partial y}) \qquad (3)$$

$$\frac{(huk)}{\partial x}+\frac{\partial(hvk)}{\partial y}=\frac{\partial}{\partial x}(h\frac{\upsilon_{ef}}{\sigma_k}\frac{\partial k}{\partial x})+\frac{\partial}{\partial y}(h\frac{\upsilon_{ef}}{\sigma_k}\frac{\partial k}{\partial y})+hG-c_D h\varepsilon+hP_{kv} \qquad (4)$$

$$\frac{(hu\varepsilon)}{\partial x}+\frac{\partial(hv\varepsilon)}{\partial y}=\frac{\partial}{\partial x}(h\frac{\upsilon_{ef}}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x})+\frac{\partial}{\partial y}(h\frac{\upsilon_{ef}}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial y})+c_1\frac{\varepsilon}{k}hG-c_2\frac{\varepsilon^2}{k}h+hP_{\varepsilon v} \qquad (5)$$

$$\upsilon_{ef}=\upsilon+\upsilon_t=\upsilon+c_\mu\frac{k^2}{\varepsilon} \qquad (6)$$

Oznake pomenijo: h - globina vode, u in v - komponenti hitrosti v x in y smeri, z_b - kota dna, n - Manningov koeficient hrapavosti, υ_{ef}, υ_t in υ - kinematični koeficienti efektivne, turbulentne in molekularne viskoznosti, g - gravitacijski pospešek, k - turbulentna kinetična energija na enoto mase in ε - stopnja njene disipacije. Izrazi za G (produkcija k zaradi vodoravnih gradientov hitrosti) ter P_{kv} in $P_{\varepsilon v}$ (izvorna člena zaradi trenja ob dno) so skupaj s konstantami v modelu turbulence (c_D, c_μ, c_1, c_2, σ_k in σ_ε) podani v literaturi (Rodi, 1980).

Notations: h – water depth, u and v – velocity components in the x and y directions, z_b - bottom elevations, n – Manning's friction coefficient, υ_{ef}, υ_t and υ - kinematic coefficients of the effective, turbulent and molecular viscosity, g - gravity acceleration, k - turbulent kinetic energy per unit mass and ε - the rate of its dissipation. The expressions of G (the production of k due to horizontal velocity gradients), P_{kv} and $P_{\varepsilon v}$ (source terms due to the bottom friction), as well as the values of the standard turbulent constants (c_D, c_μ, c_1, c_2, σ_k and σ_ε), can be found in the literature (Rodi, 1980).

2.2 ROBNI POGOJI

Pri reševanju enačb (1) do (5) potrebujemo robne pogoje na vseh štirih straneh računskega področja, saj gre zaradi vključenih difuzijskih členov z efektivno viskoznostjo za eliptičen tip problema. Za konkreten primer toka Soče smo upoštevali spodaj navedene robne pogoje, pri čemer so hitrosti v usmerjene v y smeri vzdolž toka, hitrosti u pa v smeri x prečno na tok.

Na gorvodnem robu modela so predpisane hitrosti. Vtočna hitrost v se v vsaki iteraciji izračuna tako, da vtok v model ustreza obravnavanemu stalnemu pretoku Q_0, prečna hitrost u pa se izračuna ob pogoju $\partial u / \partial y = 0$. Ker so popravki vtočnih hitrosti enaki nič, morajo biti na vtoku enaki nič tudi gradienti popravkov gladin h' v vzdolžni smeri, $\partial h' / \partial y = 0$ (Patankar, 1980; Četina, 1988). Na dolvodnem robu smo podali v prečni smeri vodoravno koto gladine z ter upoštevali, da so vzdolžni gradienti hitrosti enaki nič, torej $\partial v / \partial y = 0$ in $\partial u / \partial y = 0$. Ustrezne kote z za spodnji rob dvodimenzijskega modela smo povzeli iz poročila IBE (1997). Na vseh trdnih robovih so prečne hitrosti enake 0, za vzdolžne pa smo upoštevali veljavnost logaritemskega stenskega zakona (Četina, 1988; 1989).

Tudi za k in ε potrebujemo robne pogoje na vseh štirih robovih računskega področja. Podrobneje so navedeni v ustrezni literaturi (Rodi, 1980).

2.3 METODA REŠEVANJA IN RAČUNALNIŠKI PROGRAM PCFLOW2D

Sistem nelinearnih parcialnih diferencialnih enačb (1) - (6) rešujemo numerično z metodo končnih prostornin (Patankar, 1980; Četina, 1989). Njene temeljne značilnosti so premaknjena numerična mreža, hibridna shema (kombinacija centralnodiferenčne in sheme gorvodnih razlik) ter iteracijsko reševanje na podlagi popravkov globin. V primeru upoštevanja nestalnega toka je uporabljena polna implicitna shema (Četina, 1988).

2.2 BOUNDARY CONDITIONS

To solve the elliptic equations (1) to (5) that include terms with effective viscosity, boundary conditions were needed on all four sides of the computational domain. If we consider that velocities v are directed streamwise along the y axis, and velocities u, meanwise along the x axis, in the case of the Soča River the following boundary conditions were taken into account.

At the upstream end of the model, the velocities were prescribed. In each iteration, the inflow velocity v was computed according to the steady discharge Q_0, while the lateral velocities u were determined by the condition $\partial u / \partial y = 0$. Since inflow velocity corrections are zero, the longitudinal gradients of depth corrections h' at the upstream end are also zero, $\partial h' / \partial y = 0$ (Patankar, 1980; Četina, 1988). At the downstream end, the horizontal water surface elevation was prescribed, and the longitudinal velocity gradients were zero, $\partial v / \partial y = 0$ and $\partial u / \partial y = 0$. The appropriate surface elevations, z, at the downstream end of the two-dimensional model, were obtained from the IBE report (1997). At all solid boundaries, the normal velocities were 0 and the longitudinal velocities were computed from the logarithmic law of the wall (Četina, 1988; 1989).

The boundary conditions for k and ε that are also needed on all four boundaries of the computational domain can be found in Rodi (1980).

2.3 METHOD OF SOLUTION AND *THE PCFLOW2D COMPUTER CODE

The set of non-linear partial differential equations (1) – (6) was solved numerically by the finite volume method (Patankar, 1980; Četina, 1989). The main characteristics of the method are: a staggered numerical grid; a hybrid scheme (a combination of central-difference and upwind scheme) and an iterative procedure of depth corrections. In the case of unsteady flow computations, a fully implicit scheme is used (Četina, 1988).

Program PCFLOW2D, ki je prirejen za uporabo na osebnih računalnikih, je bil razvit na UL FGG v Ljubljani (Četina, 1988). Program se stalno izpopolnjuje z možnostjo upoštevanja novih vrst robnih pogojev, z vgradnjo novejših numeričnih metod ter z razvojem prijaznejših uporabniških vmesnikov. Simulacije za Sočo smo izvedli na računalniku s procesorjem Pentium III s frekvenco delovanja 900 MHz, tako da so kljub numerični zahtevnosti posamezni računi trajali le dobre pol ure.

Za vsak računski pretok program PCFLOW2D sam poišče spremenljive geometrijske meje računskega področja. Za dosego konvergentne rešitve je bilo povprečno potrebnih okrog 3000 iteracij pri relativni napaki, ki ne presega enega odstotka računskega pretoka skozi področje.

3. UMERJANJE MODELA

3.1 VHODNI PODATKI

3.1.1 GEOMETRIJSKI PODATKI

Za pripravo matematičnega modela struge reke, ki je bil podlaga za pridobivanje informacij o kotah dna v posameznem računskem polju, so bili uporabljeni razpoložljivi geodetski podatki, katerih viri so podrobno navedeni v strokovnem poročilu (Četina & Krzyk, 2001). Za odsek gorvodno od praga je bilo na voljo 13 prečnih profilov struge reke Soče, ki so bili posneti na medsebojni razdalji od 13 do 78 m v skupni dolžini 325 m in podani s 173 geodetsko izmerjenimi točkami, in situacijski načrt varovalnega nasipa gradbene jame strojnice HE Plave II. Za odsek dolvodno je bil za stanje pred izgradnjo praga upoštevan enakomeren padec dna v dolžini približno 200 m do kote 75.0 m n.m. Za stanje po izgradnji praga pa je bilo upoštevano poglobljeno dno struge Soče do kote 75.0 m n.m. Širina poglobljenega korita je 45 m, brežine obeh bregov so oblikovane v naklonu 1:2, dolžina poglobitve je 860 m dolvodno od iztoka HE Plave II. V primerih, kjer je bila simulirana zapolnitev prodne lovilne jame za pragom z odloženimi

The PCFLOW2D computer code was developed at the UL FGG in Ljubljana (Četina, 1988), and it was adopted to run on personal computers. Recently additional boundary conditions, new numerical methods and user-friendly interfaces have been implemented. The simulations of the Soča River flow were performed on the PC computer, with a Pentium III processor running at 900 MHz. In spite of the numerical complexity of the calculations, they took only about half an hour of the computer time.

For different discharges, the PCFLOW2D program is capable of adopting the boundaries of the computational domain automatically. To achieve the convergent solution, an average number of about 3000 iterations was needed to lower the numerical error below 1% of the total discharge.

3. MODEL CALIBRATION

3.1 INPUT DATA

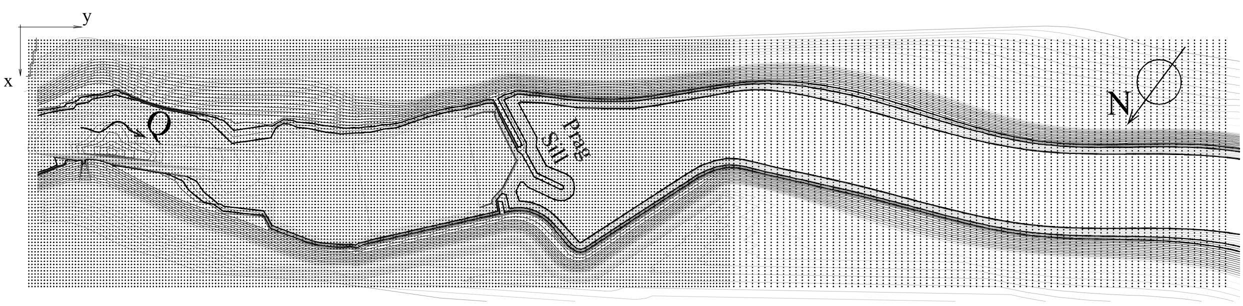
3.1.1 GEOMETRIC DATA

To prepare the digital terrain model, which has served as a basis for the information about bottom elevations in numerical cells, geodetic data from different sources were used (Četina & Krzyk, 2001). For the 325 m long Soča River reach upstream from the bottom-sill, 13 cross-section profiles were given at distances from 13 to 78 m that were surveyed with 173 geodetic points. The layout of the protective levee of the HPP Plave II powerhouse building-ground was also available. For the downstream reach before the bottom-sill construction, the uniform bottom slope was supposed to be a length of 200 m to the bottom elevation of 75,0 m above sea level. After the bottom-sill construction, an excavation of sediments to the bottom elevation of 75,0 m above sea level and a river training of the 860 m long reach downstream of the HPP Plave II outflow was performed. The channel width of 45 m and the bank slope of 1:2 was taken into account. In the cases where the fulfilment of the sediment retention capacity upstream of rinjenimi plavinami, je bilo predpostavljeno vodoravno oblikovano dno od praga do zoženega dela struge reke Soče.

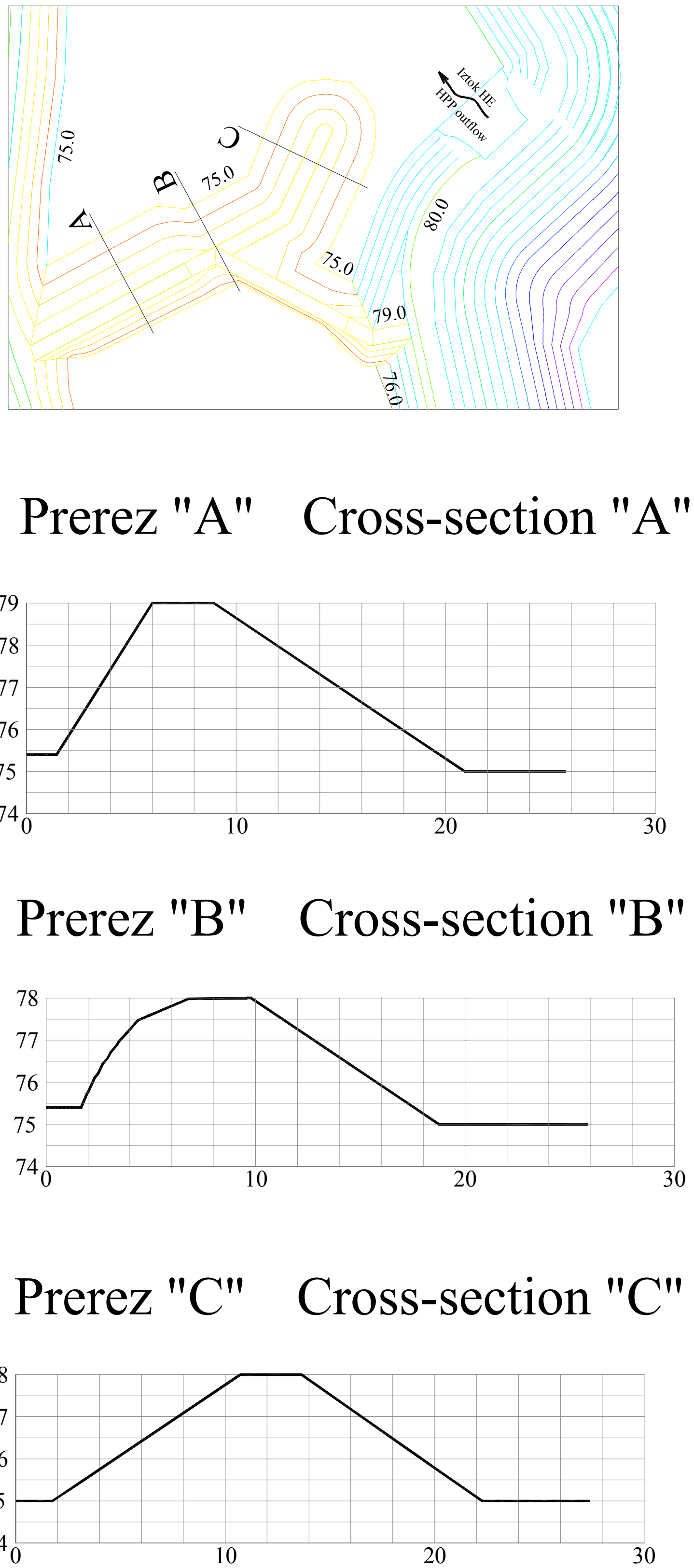
Geodetske podatke v grafični in številčni obliki je bilo treba ustrezno obdelati in pripraviti v obliki, ki bi bila najbolj primerna za nadaljnjo pripravo računalniškega modela struge. S pomočjo programa QuickSurf, ki je dodatek grafičnemu programu AutoCAD, in s pomočjo lastnih pomožnih programov za delo z geodetsko podanimi točkami, je bila oblikovana podatkovna baza izmerjenih ali projektiranih točk dna struge in brežin reke Soče ter predvidenega praga. Na podlagi izbranega načina interpolacije je nato program QuickSurf oblikoval površino struge reke in določil kote dna vseh točk numerične mreže. Uporabljena je bila razmeroma gosta neenakomerna numerična mreža z 291 točkami v vzdolžni y smeri, kjer je bila razdalja Δy = 2 m na gorvodnem delu obravnavanega območja dolžine 445 m in večja Δy = 4 m na območju 120 m dolvodno od praga do konca modela. Numerična mreža je bila v prečni x smeri enakomerna s 86 točkami (Δx = 2 m). Dolžina računskega področja (vzdolž toka) je 712 m, širina pa 169 m (slika 2). V strugi je prikazan tudi položaj praga, katerega prerez podaja slika 3.

the bottom-sill was simulated, the horizontal river bottom was approximated from the sill to the upstream narrow of the Soča River.

The raw geodetic data in graphical and numerical form had to be processed for the further preparation of the digital terrain model. With the use of the QuickSurf and AutoCAD graphic packages and our own intermediate programs to manipulate with geodetic points, a large data base of measured and designed terrain and river bed (including different shapes of the bottom-sill) points was formed. On the basis of different interpolation methods, the QuickSurf package was capable of forming the riverbed surface, and, as a final result, the bottom elevations at all points of the numerical mesh were determined. A relatively dense non-uniform numerical mesh with 291 points in the longitudinal y direction was used. The chosen space step at the 445 m long upstream part of the model was Δy = 2 m, while the space step increased to Δy = 4 m at the downstream end of the model. In the lateral x direction, a uniform mesh had 86 points with the space step Δx = 2 m. The total length of the computational domain was 712 m and the total width was 169 m (Figure 2). The cross section of the sill which is situated at the riverbed can be seen from Figure 3.



Slika 2. Računsko področje in uporabljena numerična mreža.
Figure 2. Computational domain and the numerical mesh.



Slika 3. Prečni prerez praga.
Figure 3. Cross-section of the sill.

3.1.2 HIDROLOŠKI IN HIDRAVLIČNI PODATKI

Hidrološki podatki o pretokih so povzeti po poročilu IBE (1997). V tem poročilu so obdelani pretoki Soče na območju predvidene elektrarne Plave II na podlagi hidrološke študije povodja reke Soče, ki jo je izdelal Vodnogospodarski inštitut Ljubljana (VGI, 1982). Pri analizi toka čez prag nad iztokom iz hidroelektrarne so bili upoštevani naslednji pretoki: 100, 200 in 300 m^3/s ter pretok s povratno dobo 100 let, ki znaša po omenjeni študiji 2718 m^3/s. Poleg glavnih pretokov v strugi Soče so bili pri nižjih pretokih dodatno upoštevani še iztoki iz HE Plave II do vrednosti instaliranega pretoka (105 m^3/s).

Tudi podatki o kotah gladine vode so bili povzeti po poročilu IBE (1997). Gladine pri enodimenzijskem računu zajezitve med HE Solkan, HE Plave I in HE Plave II so bile določene s pomočjo programa DRAGLA iz programskega paketa HIDRO90 (Širca, 1990). Izračuni so bili opravljeni na podlagi 42 prečnih profilov, ki jih je leta 1982 posnel Geodetski zavod Maribor, saj novejših izmer geometrije struge ni bilo na voljo. Umerjanje enodimenzijskega modela je bilo opravljeno na podlagi dveh podatkov o gladinah: kote gladine v akumulaciji Solkan in kote v profilu HE Plave I, in sicer za pretoke med 200 in 2500 m^3/s. Za različne pretoke so bili ustrezno določeni koeficienti hrapavosti. Rezultat teh računov so bile tudi kote gladine vode v posameznih profilih. Kote gladine v profilu P40 na stacionaži km 13 + 017 (sliki 4 in 5) so bile uporabljene pri določanju dolvodnega robnega pogoja za dvodimenzijski matematični model. Zadnji profil dvodimenzijskega modela leži približno 200 m dolvodno, zato so kote v tem profilu nekaj nižje kot v P40, določene pa so bile s poskusnimi računi, tako da v P40 dobimo ustrezno koto (Četina & Krzyk, 2001).

Uporabljeni dvodimenzijski matematični model nam dopušča možnost podajanja različnih vrednosti koeficienta hrapavosti po posameznih podpodročjih. Vendar bi za njegovo natančno določanje potrebovali

3.1.2 HYDROLOGIC AND HYDRAULIC DATA

The hydrologic data about discharges was taken from the IBE report (1997). The characteristic discharges of the Soča River in the HPP Plave II cross-section were elaborated on the basis of the hydrologic study of the Soča River basin, which was performed by the Water Management Institute in Ljubljana (VGI, 1982). At the flow analysis over the sill, the following discharges were taken into account: 100, 200 and 300 m^3/s, and the flood discharge 2718 m^3/s, which has a return period of 100 years. At lower discharges, the additional outflow from the HPP Plave II in the amount of 105 m^3/s was also considered.

The data about water surface elevations were also taken from the IBE report (1997). The one-dimensional calculations of the backwater effect between the HPP Solkan, the HPP Plave I and the HPP Plave II were performed using the DRAGLA computer code from the HIDRO90 program package (Širca, 1990). Due to a lack of more recent data, the calculations were made on the basis of 42 cross-sectional profiles that had been measured by the Geodetic service, Maribor, in 1982. For discharges between 200 to 2500 m^3/s, the calibration of the one-dimensional model was performed by the comparison with measured water surface elevations in the Solkan reservoir and the HPP Plave I cross-section. With calibrated friction coefficients, the water surface elevations were computed at different discharges. The water surface at the P40 cross-section (km 13 + 017, Figures 4 and 5), served as the downstream boundary condition for the two-dimensional mathematical model. Since the last cross-section of the two-dimensional domain was located about 200 m downstream from P40, the boundary water surface elevations were slightly lower, and obtained by trial and error calculations (Četina & Krzyk, 2001).

In the two-dimensional model which was used, it was possible to prescribe different friction coefficients for the sub-areas. To determine the coefficients more accurately, terenske meritve hitrosti in gladin pri visokih vodah, ki bi bile bolj natančne in bolj zanesljive od razpoložljivih. V študiji toka reke Soče z enodimenzijskim matematičnim modelom so bile uporabljene okvirne vrednosti koeficienta hrapavosti po Manningu v mejah n = 0,041 - 0.059 sm$^{-1/3}$ (IBE, 1997), ki so bile določene za pretoke od 200 do 1600 m^3/s. Glede na te vrednosti, značilnosti struge reke Soče na obravnavanem odseku s predlaganimi vrednostmi iz literature in predvsem glede na dosedanje izkušnje z nekoliko nižjimi koeficienti hrapavosti pri dvodimenzijskih modelih, so bile za začetno umerjanje uporabljene vrednosti za n med 0.03 in 0.05 sm$^{-1/3}$.

3.2 POSTOPEK UMERJANJA

Umerjanje matematičnega modela pomeni predvsem postopek, pri katerem določimo porazdelitev koeficientov hrapavosti v strugi. Po določitvi okvirnih fizikalnih mej (podpoglavje 3.1.2) smo točnejšo vrednost koeficienta hrapavosti za obravnavano območje določili z upoštevanjem naslednjih dejavnikov: terenskega ogleda, naših dosedanjih izkušenj, primerjave rezultatov dvodimenzijskega izračuna z enodimenzijsko izračunanimi kotami z modelom DRAGLA in primerjave izračunanih kot gladine vode z merjenimi vrednostmi.

Pri pretokih do 500 m^3/s smo umerjanje izvedli predvsem na podlagi primerjave gladin z ustreznimi enodimenzijskimi računi IBE (1997). Za določitev koeficienta hrapavosti pri višjih pretokih pa smo se najbolj opirali na podatke Soških elektrarn o izmerjenih gladinah ob nasipu gradbene jame pri visoki vodi v oktobru 2000, ko je pretok dosegel Q = 1700 m^3/s. Pri umerjanju so bili smiselno uporabljeni tudi razpoložljivi podatki Vodnogospodarskega inštituta o sledovih visoke vode na levem bregu, predvsem za približno ugotavljanje poteka gladin tudi v prečni smeri. Končni rezultat umerjanja pri Q = 1700 m^3/s in pri upoštevanju nasipa gradbene jame je razviden iz slik 4 (hitrostno polje) in 5 (kote gladin v prečnih in podolžnih

additional field measurements of velocities and surface elevations at flood discharges were needed. One-dimensional calculations of the Soča River flow were performed with the Manning's friction coefficient values from n = 0,041 to 0,059 sm$^{-1/3}$ (IBE, 1997) for discharges between 200 and 1600 m^3/s. According to these values, the characteristics of the Soča riverbed on the investigated area, proposed values from the literature and our previous experiences with the behaviour of two-dimensional models, which usually require lower friction coefficients, we started the calibration process with values between n = 0.03 and 0.05 sm$^{-1/3}$.

3.2 CALIBRATION PROCESS

The main aim of the calibration process was to find out the distribution of friction coefficients in the riverbed. After the rough limits were set (chapter 3.1.2), more accurate values of the roughness coefficients were determined by taking into account the following factors: field examinations; the comparison between the results of the two-dimensional model with water surface elevations obtained by the one-dimensional DRAGLA model and the comparison between the computed and measured water levels.

At discharges below 500 m^3/s, the calibration was mainly performed by the comparison of water levels with one-dimensional computations (IBE, 1997). To determine friction coefficients at higher discharges, we relied on the data about water levels near the protective levee that were recorded by the "Soča River Hydro Power Plants" company at the flood discharge Q = 1700 m^3/s. During the calibration process, available data about flood signs at the left bank, obtained by the Water Management Institute, were also taken into account. They were mainly used to assess the shape of the water surface in the lateral direction. The final result of the calibration process at Q = 1700 m^3/s and for the case with the protective levee can be seen from Figure 4 (velocity field) and Figure 5 (computed and measured water profilih vzdolž ravnih linij z vrisanimi merjenimi gladinami). Na levem bregu je bila med profiloma P40.4 in P40.5 izmerjena kota gladine z = 85.05 m in izračunana z = 85.06 m, med profiloma P40.6 in P41 pa izmerjena z = 85.35 m in izračunana z = 85.34 m. Merjene in izračunane kote gladin na desnem bregu so bile z = 85.25 m in z = 85.27 m (približno v profilu P40.5) ter z = 85.41 m in z = 85.47 m (med profiloma P40.6 in P41). Na podolžnem profilu gladin sta med prečnima profiloma P40.6 in P41 vnešeni izmerjeni koti z = 85.35 m (levo) in z = 85.41 m (desno), izračunani koti blizu levega in desnega brega pa sta bili z = 85.32 m in z = 85.46 m. Izbrana koeficienta hrapavosti, ki smo jih nato uporabili pri nadaljnjih računih, sta bila n = 0.05 sm$^{-1/3}$ za pretoke do Q = 500 m^3/s in n = 0.04 sm$^{-1/3}$ za višje pretoke.

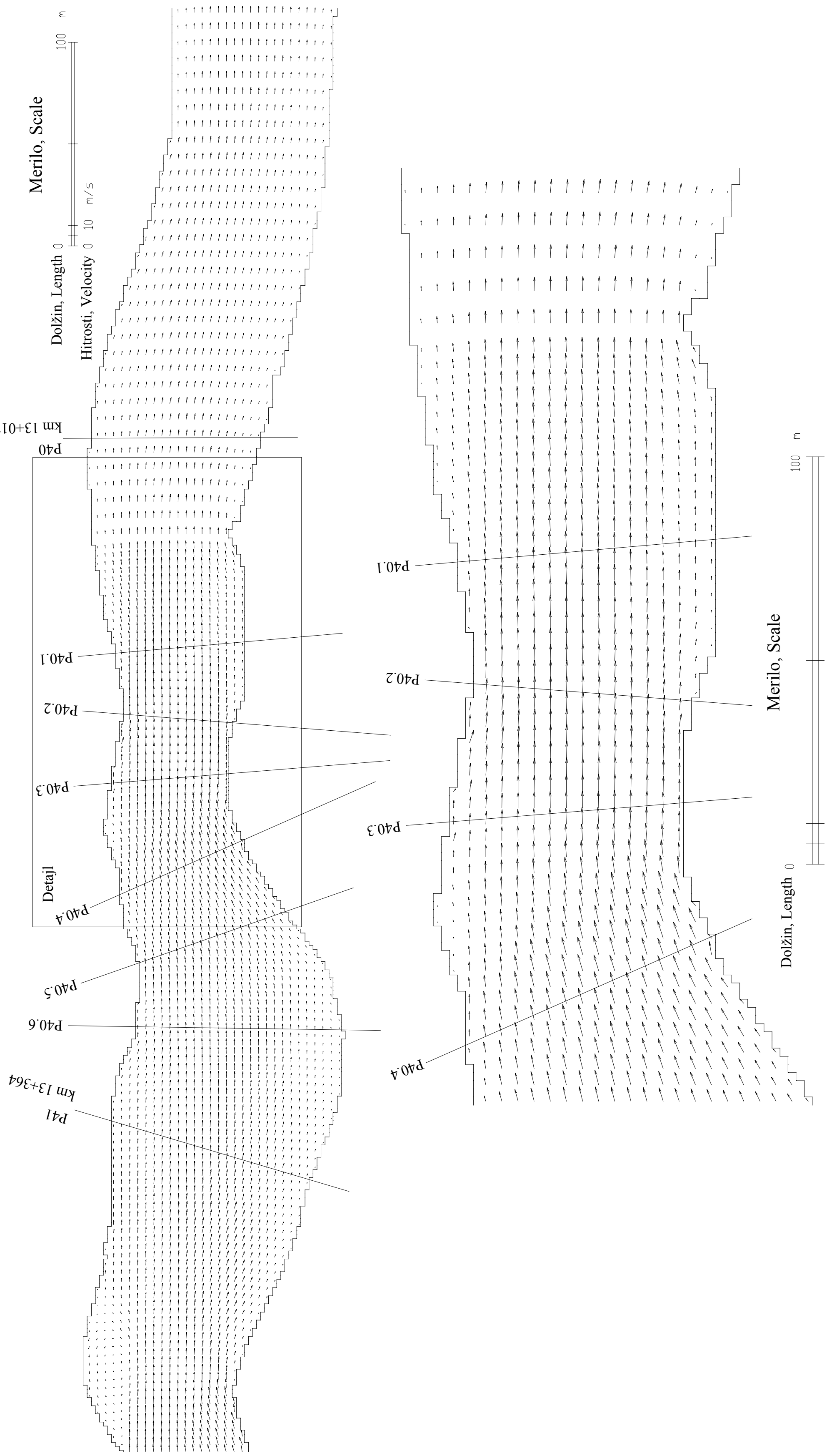
Točnost uporabljenega modela je, glede na to, da lahko zajamemo tok v dveh dimenzijah, razmeroma dobra. Pri točnih vhodnih hidroloških, hidravličnih in geometrijskih podatkih ocenjujemo, da bi bila točnost modela na obravnavanem odseku pri nizkih pretokih do Q = 500 m^3/s v mejah ± 5 cm, pri stoletnem pretoku Q_{100} pa v mejah ± 10 cm. To je hkrati tudi natančnost, s katero lahko ugotavljamo vplive relativnih sprememb gladine zaradi različnih ukrepov v strugi (predvsem oblike in višine praga ter poglobitve struge) glede na izbrano referenčno stanje.

Vendar pa največjo napako vnesemo v račun z netočnimi vhodnimi podatki. Kot je pokazalo umerjanje, imamo v primeru Soče na območju iztoka HE Plave II, kljub geometrijskim in geodetskim podatkom o topografiji struge in terena, na voljo premalo natančne podatke o spodnjem robnem pogoju ter relativno malo zanesljivih meritev gladin (v samo štirih točkah). Ker pa gre za relativno kratek odsek, na podlagi umerjanja ocenjujemo, da je točnost izračunanih absolutnih kot na odseku med ± 15 cm pri Q = 1700 m^3/s in ± 20 cm pri Q_{100} = 2718 m^3/s.

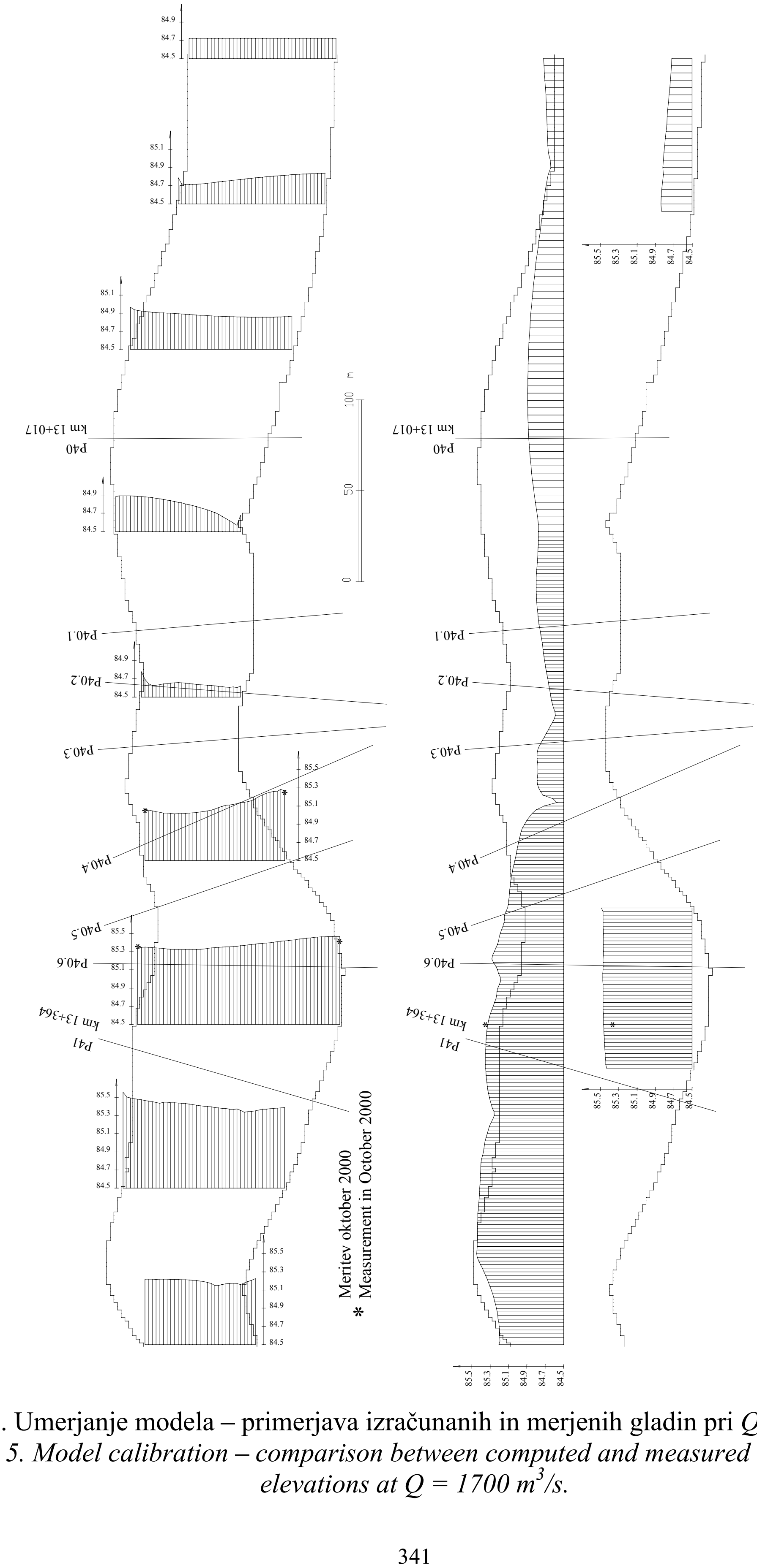
surface elevations in cross-section and longitudinal profiles along straight lines). At the left bank, between cross-sections P40.4 and P40.5, measured and computed water surface elevations were z = 85.05 m and z = 85.06 m, respectively, and between cross-sections P40.6 and P41, z = 85,35 m (measured) and z = 85.34 m (computed). The measured and computed water surface elevations at the right bank were z = 85.25 m and z = 85.27 m (approx. in the cross-section P40.5) and z = 85.41 m and z = 85.47 m (between the cross-sections P40.6 and P41). At the longitudinal water surface profile, the measured elevations z = 85.35 m (left) and z = 85.41 m (right) between cross-sections P40.6 and P41 are marked, while the computed values near the left and right banks were z = 85.32 m and z = 85.46 m, respectively. The calibrated friction coefficients for further computations were n = 0.05 sm$^{-1/3}$ for discharges below 500 m^3/s, and n = 0.04 sm$^{-1/3}$ for higher discharges.

Since it was possible to simulate flow in two dimensions, the accuracy of the model is relatively high. If the input hydrologic, hydraulic and geometric data were exact, the accuracy of the model would be ± 5 cm at lower discharges, and below 500 m^3/s and ± 10 cm at Q_{100} = 2718 m^3/s. With this accuracy it is possible to investigate changes of water levels, relative to the reference state, due to different training measures in the riverbed (particularly the shape and height of the bottom-sill and the deepening of the river bed).

But the largest error could be introduced by the inexact input data. The calibration process in the case of the Soča River near the HPP Plave II outflow showed the lack of certain data. In spite of geometric and geodetic riverbed and terrain data, more accurate water levels at the downstream end of the model and more reliable measurements during floods would be needed (water levels in 4 points were available only). But since the simulated reach is relatively short, the calibration process suggests that the accuracy of the computed absolute water surface elevations are between ± 15 cm at Q = 1700 m^3/s and ± 20 cm at Q_{100} = 2718 m^3/s.



Slika 4. Umerjanje modela – izračunano hitrostno polje pri pretoku Q = 1700 m^3/s.
Figure 4. Model calibration – computed velocity field at the discharge Q = 1700 m^3/s.



Slika 5. Umerjanje modela – primerjava izračunanih in merjenih gladin pri Q = 1700 m^3/s.
Figure 5. Model calibration – comparison between computed and measured water surface elevations at Q = 1700 m^3/s.

4. REZULTATI IZRAČUNOV

Po že opisanem umerjanju modela pri pretoku Q = 1700 m^3/s je bil ob upoštevanju nasipa gradbene jame in brez poglobitve struge dolvodno od iztoka izveden še primer računa s Q_{100} = 2718 m^3/s. Ta račun smo potem uporabili kot referenčno stanje, s katerim so bili primerjani končni računi. Kot končno stanje je bila upoštevana odstranitev nasipa gradbene jame, različne različice položaja in oblike talnega pragu in horizontalna poglobitev struge dolvodno do kote 75.00 m, dokler se ne vklopi v obstoječe dno struge. Pregled vseh simuliranih primerov in izračunanih hitrostnih polj je podan v poročilu Četina & Krzyk (2001), kjer je podrobno opisana tudi izbira končne oblike talnega praga. V tem poročilu so na slikah 6 do 10 grafično prikazani samo nekateri najznačilnejši rezultati za končno obliko pragu in pretoke 100, 200, 300 in 2718 m^3/s.

4.1 POLJE HITROSTI

Izračunani vektorji globinsko povprečnih hitrosti za posamezne primere nam povedo, ali je rešitev s talnim pragom ustrezna za preprečitev odlaganja rinjenih plavin na območju iztoka HE Plave II. Na slikah 6, 7 in 8 so vektorji izrisani v vsaki drugi točki numerične mreže tako v x kot tudi y smeri. Pri pretoku Soče Q = 100 m^3/s brez delovanja turbine (slika 6) ter pretoku Q = 300 m^3/s ob hkratnem delovanju turbine (+ 105 m^3/s, slika 7) so lepo vidne značilnosti toka preko praga. Zlasti v znižanem delu ob desnem bregu so hitrosti povečane, tako da preprečujejo morebitno odlaganje rinjenih plavin.

Za oceno strižnih napetosti ob dnu pri različnih pretokih so pomembne velikosti hitrosti. Pri Q = 100 m^3/s največje globinsko povprečne hitrosti nastopajo na hrbtu praga ob desnem bregu in znašajo približno 1.6 m/s (slika 6), v preostalem delu struge pa je razpored hitrosti bolj enakomeren z vrednostmi med 1.1 in 1.3 m/s. Pri Q_{100} = 2718 m^3/s pa so hitrosti med 3 in 4 m/s (slika 8). Najmanjše ali celo povratne gorvodno usmerjene hitrosti pa nastopajo na recirkulacijskih območjih (največje je dolvodno od talnega praga ob levem bregu), kjer je mogoče pričakovati odlaganje rinjenih plavin.

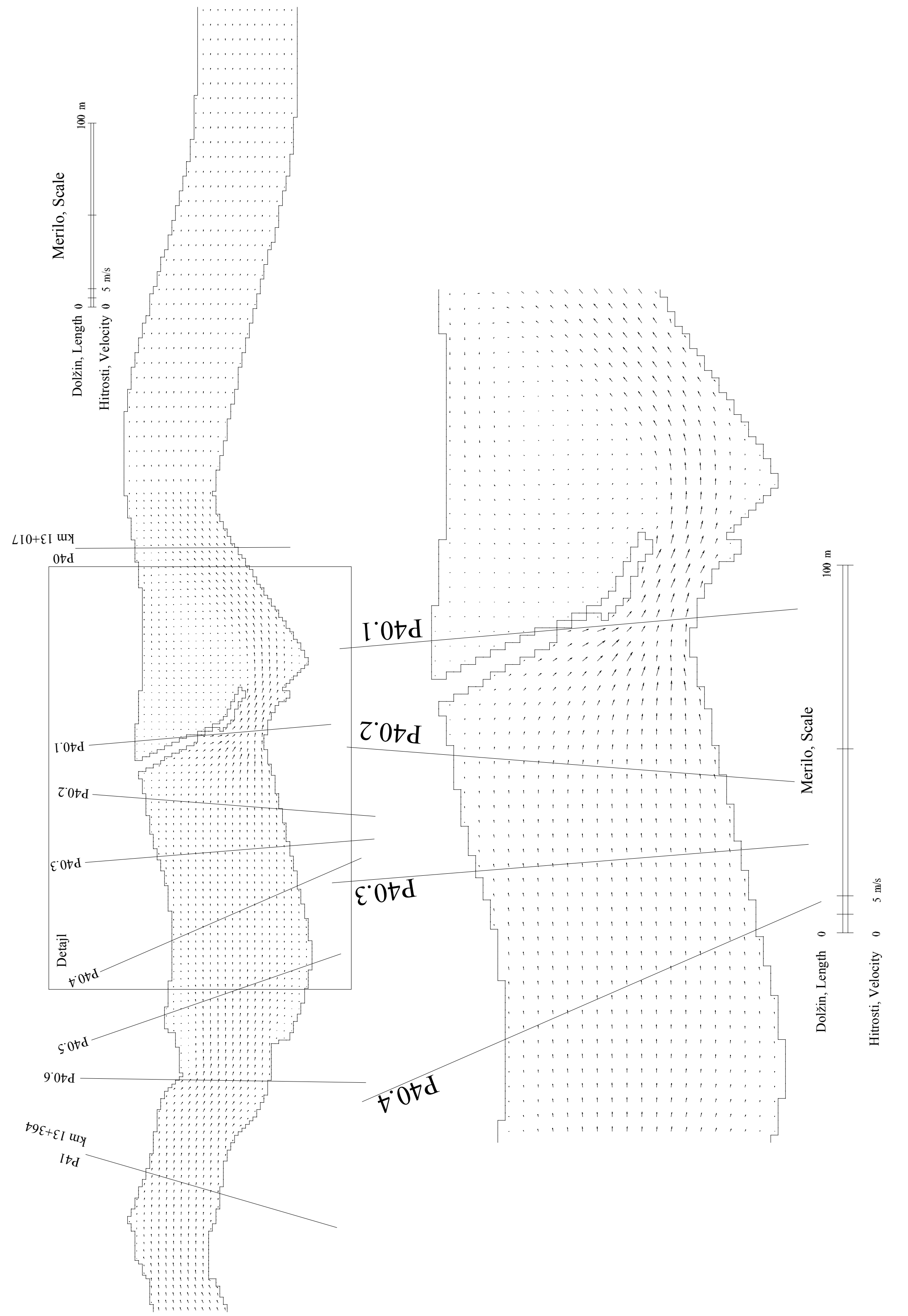
4. COMPUTATIONAL RESULTS

After the model had been calibrated at Q = 1700 m^3/s, the case with protective levee and without riverbed deepening could be computed at a discharge of Q_{100} = 2718 m^3/s. This case was chosen as a reference state to be compared with final computations. In the final state, the removal of the protective levee, different layouts and shapes of the bottom-sill and the horizontal riverbed profile downstream to the bottom elevation of 75.00 m above sea level were considered. The review of all simulated cases and computed velocity fields can be found in the report Četina & Krzyk (2001), where the choice of the final shape of the bottom-sill is explained in detail. Here only, some most significant graphical results for the final shape of the bottom-sill are shown in Figures 6 to 10, for the discharges 100, 200, 300 and 2718 m^3/s.

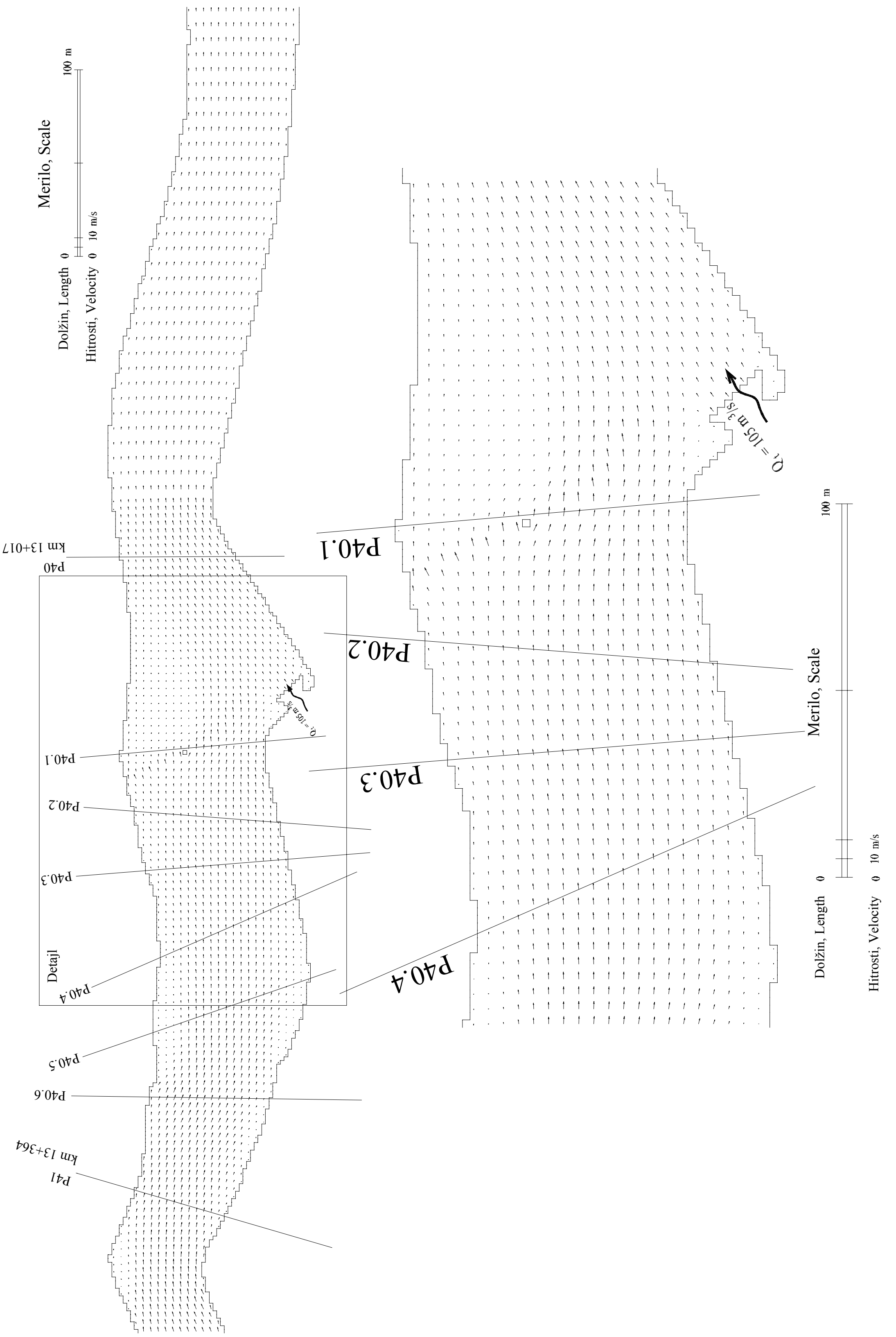
4.1 VELOCITY FIELD

The computed velocity vectors for different cases could indicate whether the solution with the bottom-sill is appropriate to prevent sedimentation in the area of the HPP Plave II outflow. In Figures 6, 7 and 8, the velocity vectors were plotted in every second point of the numerical grid in the x and y directions, respectively. At the Soča River discharge Q = 100 m^3/s without turbine operation (Figure 6) and at the discharge Q = 300 m^3/s, with turbine operation (+ 105 m^3/s, Figure 7), the characteristics of the flow over the sill could be clearly seen. The higher velocities near the right bank over the lower part of the sill prevented sedimentation.

Magnitudes of the velocities were important in assessing bottom shear stresses. At Q = 100 m^3/s, the maximum values of depth-averaged velocities near the right bank on the downstream part of the sill were about 1,6 m/s (Figure 6). In another part of the river, the velocity distribution was more uniform, with values between 1,1 and 1,3 m/s. At Q_{100} = 2718 m^3/s, velocities were between 3 and 4 m/s (Figure 8). Minimum or even upstream-directed velocities could be indicated in the recirculation zones. In the largest recirculation zone, just downstream of the sill near the left bank, sedimentation could be expected.



Slika 6. Izračunano hitrostno polje pri pretoku Soče Q = 100 m^3/s brez delovanja turbine.
Figure 6. Computed velocity field at the Soča River discharge Q = 100 m^3/s without turbine operation.



Slika 7. Izračunano hitrostno polje pri pretoku Soče Q = 300 m^3/s in delovanju turbine (+ 105 m^3/s).
Figure 7. Computed velocity field at the Soča River discharge Q = 300 m^3/s with turbine operation (+ 105 m^3/s).

Slika 8. Izračunano hitrostno polje pri pretoku Soče Q_{100} = 2718 m^3/s.
Figure 8. Computed velocity field at the Soča River discharge Q_{100} = 2718 m^3/s.

4.2 KOTE GLADIN

Poleg hitrostnih polj nas kot končni rezultat izračunov zanimajo tudi kote gladine pri različnih visokovodnih pretokih in predvidenih spremembah v strugi Soče na območju iztoka HE Plave II. Ker dvodimenzijski model omogoča izračun gladin v vsaki "aktivni" celici razmeroma goste numerične mreže (aktivnih je približno polovica od skupno 86 x 291 točk, kar je še vedno okrog 12 500 točk), lahko postane spremljanje številčnih podatkov o kotah gladine zelo zamudno in nepregledno. Zato so rezultati prikazani grafično v karakterističnih prečnih in podolžnih profilih, izometrična slika pa omogoča lažjo prostorsko predstavo o poteku gladine.

Primerjava kot gladin pri Q_{100} = 2718 m^3/s med končnim in referenčnim stanjem (slika 9) kaže, da končno stanje po izgradnji talnega praga zaradi hkratne odstranitve nasipa gradbene jame ne poslabšuje hidravličnih razmer gorvodno. Računi so pokazali, da se bo kota pri hišah ob levem bregu približno 100 m gorvodno od profila P41 znižala z 88.67 m n.m. med gradnjo strojnice HE Plave II na 88.23 m n.m. po odstranitvi nasipa. Torej bo kljub že upoštevanem zasipavanju dna do kote krone praga celo za 0.44 m nižja kot med gradnjo strojnice.

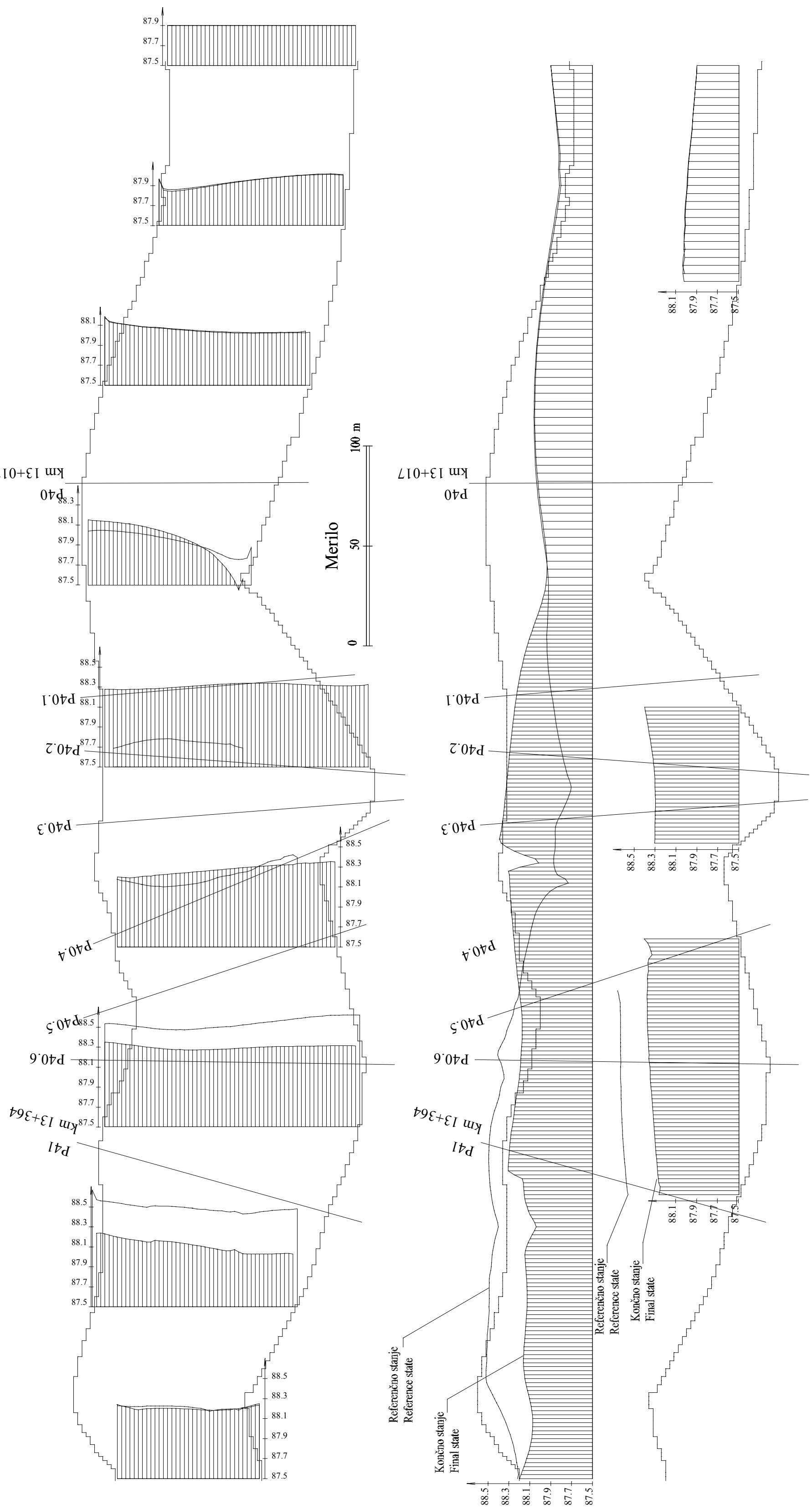
Izometrična slika gladine pri Q_{100} = 2718 m^3/s je podana na sliki 10. Pri tem je treba poudariti, da teren v suhih nesodelujočih celicah zunaj struge ne predstavlja dejanske topografije, temveč je umetno ravno odrezan, da je bolje viden potek izračunane gladine v strugi.

4.2 WATER SURFACE ELEVATIONS

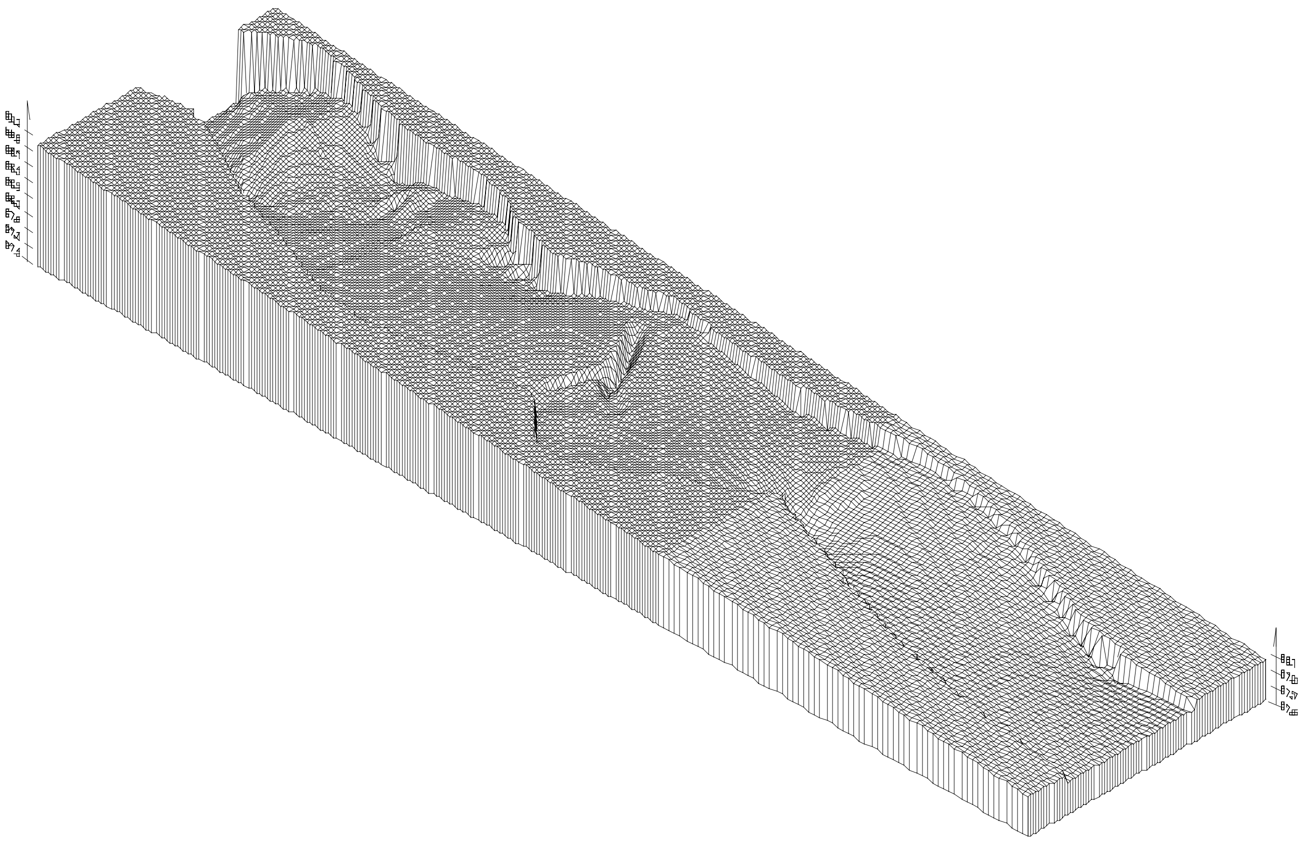
Besides velocity fields in the HPP Plave II outflow area an interesting final result was also the water surface elevations at various flood discharges, and the different changes in the Soča riverbed. Since, with a two-dimensional model, it is possible to compute the water surface in every "active" cell of a relatively dense numerical grid (about half of total 86 x 291 points were active, approximately 12 500 points), the interpretation of the numerical values about water levels could become very unpleasant and difficult to scan. For that reason the results are shown graphically in characteristic cross-sections and longitudinal profiles. The isometric view of the water surface is also added.

The comparison of water surface elevations at Q_{100} = 2718 m^3/s for the final and reference state (Figure 9) show that, in spite of bottom-weir construction due to the simultaneous protective levee removal, the hydraulic conditions upstream would not be worsened. The computations showed that the water surface elevation near the houses at the left bank approximately 100 m upstream from the P41 profile would decrease from 88.67 m to 88.23 m above sea level after the protective levee was removed. So it would be, in spite of the sediment deposition up to the sill crest, even 0.44 m lower than during the HPP Plave II powerhouse construction.

The isometric view of the water surface at Q_{100} = 2718 m^3/s can be seen in Figure 10. It was added to stress that the terrain elevations in dry cells are not realistic, but cut off at certain levels to improve the visibility of the computed water surface in the river.



Slika 9. Primerjava gladin pri pretoku Soče Q = 2718 m^3/s med referenčnim in končnim stanjem.
Figure 9. The comparison of water surface elevations between the reference and final state at the Soča River discharge Q = 2718 m^3/s.



Slika 10. Izometrična slika izračunane gladine pri pretoku Soče Q = 2718 m^3/s.
Figure 10. Isometric view of the computed free surface at Q = 2718 m^3/s.

5. ZAKLJUČKI

Z dvodimenzijskim globinsko povprečnim modelom PCFLOW2D je bil preračunan odsek Soče na območju turbinskega iztoka HE Plave II. Potem, ko je bil model zadovoljivo umerjen, je bilo s simulacijami pri nižjih pretokih Soče preverjenih več različic poglobitev struge ter tlorisnega in višinskega položaja talnega praga gorvodno od iztoka. Ocenjen je bil tudi vpliv praga na gladine pri visokovodnem pretoku Q_{100} = 1718 m^3/s.

Rezultati računov pri nizkih pretokih od 100 do 300 m^3/s z upoštevanjem delovanja turbine (+ 105 m^3/s) ali brez so pokazali, da predlagana rešitev s talnim pragom razmeroma učinkovito rešuje problem odlaganja rinjenih plavin na območju turbinskega iztoka. Zaradi padanja kote krone praga proti desnemu bregu so namreč hitrosti dolvodno ob desnem bregu povečane, kar preprečuje recirkulacijo vode in s tem odlaganje plavin. Variantni izračuni hitrostnega polja so tudi omogočili optimizacijo končne oblike praga (sliki 2 in 3).

Druga pomembna ugotovitev je, da predvideni prag pri visokih pretokih Soče (Q_{100} = 2718 m^3/s) ne poslabšuje hidravličnih razmer gorvodno, glede na obstoječe referenčno stanje pri zgrajenem nasipu gradbene jame. Po izgradnji praga in dokončanju strojnice je bil namreč nasip odstranjen, ustrezno pa je bila urejena tudi desna brežina.

Računi razpoložljivih prostornin za odlaganje rinjenih plavin gorvodno od praga so pokazali vrednosti okrog 10 000 m^3/s. To seveda ne zadostuje za zadrževanje letnih količin rinjenih plavin Soče, ki so bistveno višje, še zlasti po zadnjem potresu v Posočju in katastrofalnem drobirskem toku v Logu pod Mangartom. Del proda bo zato potoval preko praga in se odlagal ob levem bregu v zatišnem delu korita. Zato bo potrebno občasno čiščenje tega odseka, ki ga bo mogoče izvesti deloma s hidravličnim izpiranjem ob denivelaciji HE Solkan in deloma z neposrednim bagranjem korita. Na primernih lokacijah gorvodno od obravnavanega odseka je treba predvideti lovilne jame za prod.

5. CONCLUSIONS

The reach of the Soča River in the area of the HPP Plave II powerhouse outflow was computed using the two-dimensional depth-averaged model PCFLOW2D. After the model had been satisfactorily calibrated, several variants of the riverbed deepening with different layouts and crest elevations of bottom-sill were simulated at low discharges. The influence of the sill on the water levels upstream was also assessed at the flood discharge Q_{100} = 2718 m^3/s.

The computational results at low discharges from 100 to 300 m^3/s, with (+ 105 m^3/s) or without the turbine operation, proved that the bottom sill could efficiently prevent the deposition of bed-load in front of the outflow. Due to the lower crest elevations on the right part of the sill, the higher velocities near the right bank prevent water recirculation, and thus the deposition of sediments. Several alternative computations of the velocity field enabled the optimisation of the final shape of the sill (Figures 2 and 3).

Secondly, at high discharges of the Soča River (Q_{100} = 2718 m^3/s), the designed sill did not worsen the hydraulic conditions upstream according to the reference state with the protective levee of the powerhouse. This is because after the bottom-sill construction and the finishing of the powerhouse building, the levee was removed. The trained right bank also improved the situation.

The retention capacity for sediment deposition upstream of the sill was computed to be about 10 000 m^3. Certainly this is not enough to stop the evidently higher sediment inflow of the Soča River, especially after the last earthquake disaster in the Posočje region and the catastrophic debris flow at the upstream-located village of Log pod Mangartom. Part of the bed-load is thus expected to flow over the sill and to deposit just downstream near the left bank of the Soča River. Occasionally it will be necessary to remove the deposited material, either with hydraulic flushing by lowering the downstream water level, or by excavation. Some additional sediment retention basins at the upstream locations are also needed.

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