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Dvodimenzijsko modeliranje gibanja drobirskega toka v Logu pod Mangartom kot primer nenewtonske tekočine

Two-Dimensional Modelling of Debris-Flow Movement in Log pod Mangartom as an Example of a Non-Newtonian Fluid

Matjaž Četina - Mario Krzyk

Z matematičnimi modeli je bilo simulirano gibanje drobirskega toka, ki je nastal po sprožitvi plazu Stože, novembra 2000, in razdejal del vasi Log pod Mangartom. Na zgornjem delu vplivnega področja, kjer se je drobirski tok v glavnem gibal po ozkem kanjonu, je bil uporabljen enodimenzijski model DEBRIF1D. Za izbrane primere mogočih prihodnjih plazov so bili tako določeni hidrogrami pretokov drobirskega toka na zgornjem koncu ogrožene vasi Log pod Mangartom. Dvodimenzijske simulacije drobirskega toka v vasi so bile narejene z dvema modeloma: s PCFLOW2D, ki je bil razvit na FGG Univerze v Ljubljani in s tržnim modelom FLO-2D. Vsi trije modeli so bili uspešno umerjeni s terenskimi meritvami dosega plazu, pri čemer so bili upoštevani tudi rezultati geomehanskih laboratorijskih raziskav. Narejena je bila analiza občutljivosti dvodimenzijskega modela PCFLOW2D na gostoto numerične mreže in različna robna pogoja na iztoku iz področja. Veljavnost kvadratne enačbe, ki izraža trenje pri Binghamovem plastičnem modelu nenewtonske tekočine, je bila potrjena tudi pri spreminjajočem se režimu toka. Modeli so bili uspešno uporabljeni za določitev ukrepov za zaščito vasi Log pod Mangartom. Najbolj učinkovit ukrep je odstranitev drobirskih mas, ki so se odložile po zadnjem plazu v strugi in ob njej vzdolž vasi, tako da bi se morebitni novi drobirski tokovi lahko gibali mimo vasi ali imeli prostor za odlaganje.

(Ključne besede: tokovi drobirski, modeli matematični, tekočine nenewtonske, urejanje hudournikov)

Mathematical models have been used for simulations of the landslide (debris flow) below Stože that occurred in November 2000, and destroyed part of the village of Log pod Mangartom. The one-dimensional model, DEBRIF1D, was first used for simulations along the upper part of the affected region, where the debris flow was mainly in a narrow canyon. Hydrographs of the debris-flow discharge at the upstream end of the affected village of Log pod Mangartom were thus determined for possible future landslides. Two-dimensional simulations of the debris flow in the village were carried out using two models: PCFLOW2D, developed at the University of Ljubljana; and a commercial model, FLO-2D. The three models were successfully calibrated using field measurements of the debris-flow inundation limits, taking into account the results of geo-mechanical laboratory experiments. The sensitivity analysis of the two-dimensional model PCFLOW2D with different grid sizes and two different outflow boundary conditions was also made. The validity of the quadratic equation expressing the resistance of the non-Newtonian Bingham plastic fluid model was roughly confirmed, even for changing flow regimes. The models were used successfully to determine the measures for the future protection of the village of Log pod Mangartom. The most effective measure is the removal of debris mass, which was deposited after the last landslide in the stream along side the village, so that the future debris flows will move through or will be deposited.

(Keywords: debris flow, mathematical models, non-Newtonian fluids, torrent control)

0 UVOD

Blatni in drobirski tokovi, ki lahko nastanejo po sprožitvi plazov v hribovitih področjih, često povzročijo veliko materialno škodo in celo žrtve. V Sloveniji je približno tretjina ozemlja pokrita s strmimi

0 INTRODUCTION

Landslide-induced mud/debris flows are often the cause of a significant loss of property and casualties in mountainous regions. In Slovenia, approximately one third of the country is covered by pobočji, ki so samo pogojno stabilna. Zaradi neugodne geološke sestave na njih pogosto prihaja do plazov, ki jih lahko povzročijo potresi ali intenzivne padavine [12]. Znanstveniki si prizadevajo razviti zanesljive numerične modele, s katerimi bi bilo mogoče napovedati doseg možnih plazov in določiti učinke različnih varovalnih ukrepov.

Pojav blatnih in drobirskih tokov je podoben nestalnemu toku vode, posebej valovom zaradi porušitev pregrad, in do neke mere tudi dinamiki snežnih plazov [17]. V vseh primerih se tok ravna po fizikalnih zakonih ohranitve mase in gibalne količine. Znano pa je, da je trenjski upor pri gibanju drobirskega toka in snežnega plazu bolj zapleten kakor pri vodnem toku [13]. Reološko obnašanje toka je v veliki meri odvisno od koncentracije sedimentov v vodi. Glede na to razmerje lahko prihaja do skoraj suhih plazov, drobirskih tokov, blatnih tokov in toka čiste vode [1]. Koncentracija se vzdolž poti drobirskega toka zaradi vnosa dodatnih sedimentov in/ali povečanega dotoka vode s pritoki pogosto spreminja, kar simulacije toka še otežuje.

V prispevku je prikazano eno- in dvodimenzijsko modeliranje drobirskega toka, do katerega je prišlo novembra 2000 v vasi Log pod Mangartom. Tragični dogodek razmeroma velikega obsega z začetno maso plazu 1,200.000 m^3 je zahteval sedem življenj in povzročil veliko materialno škodo v vasi Log ([6], [9], [10] in [11]). Podani so opis tega dogodka ter razvoj, umerjanje in preverjanje uporabljenih matematičnih modelov. Prikazani in ocenjeni so rezultati simulacij možnih prihodnjih drobirskih tokov, v sklepih pa so predlagani nekateri najbolj učinkoviti ukrepi za zaščito vasi Log pod Mangartom.

slopes, which are conditionally stable due to their unfavourable geological composition, and are often threatened by landslides caused, e.g. by earthquakes or heavy rainfalls [12]. Scientists are trying to develop reliable numerical models that are able to predict inundation limits for possible future landslides and to determine the effect of different protective measures.

The phenomenon of mud/debris flow is similar to the unsteady flow of water, in particular to dam-break flow, and also to snow avalanche dynamics [17]. In all these cases the flow is governed by the physical laws of conservation of mass and of momentum. However, it is well known that the resistance to flow movement is more complex in debris flows and snow avalanches than in pure water flows [13]. The rheological behaviour of the flow depends to a large extent on the debris-flow sediment/water concentration. This can range from nearly dry landslides to debris flows, mud flood and pure water flows [1]. The concentration often changes along the debris path, as additional sediment is scavenged into the flow and/or additional water streams join the debris flow, which makes the simulations even more difficult.

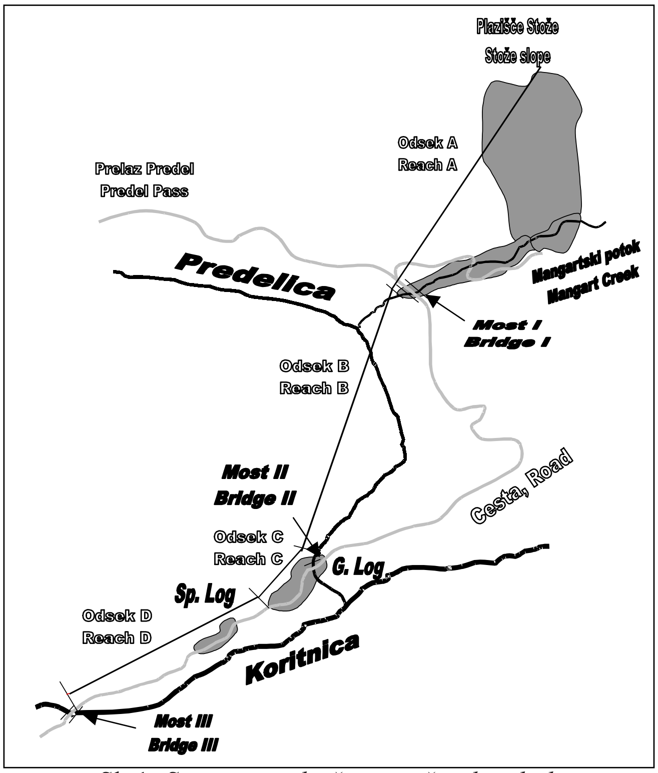
One- and two-dimensional mathematical modelling of the debris flow that occurred in November 2000 at the village of Log pod Mangartom is presented. This tragic event involved an initial landslide mass of 1.200,000 m^3 and resulted in the loss of seven lives and a lot of property ([6], [9], [10] and [11]). The paper includes a description of this event as well as the development, the calibration and the validation of the mathematical models used. The results of possible future debris-flow simulations are discussed and in the conclusions some of the most effective protective measures for the village of Log pod Mangartom are proposed.

1 OPIS DOGODKA POJAVA DROBIRSKEGA TOKA

Dne 15. novembra leta 2000 se je na pobočju pod Stožami utrgal zemeljski plaz, ki je zdrsnil do mostu v Mlinču (most I), ga le delno prelil, večina mase pa se je ustavila nad mostom (odsek A, sl. 1). Po dvodnevnem močnem deževju in zaradi vtoka Mangartskega potoka se je plazovina zelo razmočila. Nekaj po polnoči 17. novembra je na pobočju pod Stožami očitno zdrsnil dodatni manjši plaz. Drsel je do razmočenega prvega, tega ponovno sprožil v gibanje, nato pa je skupna masa drobirskega toka prelila in odnesla most I ter zdrvela prek ozkega kanjona Mangartskega potoka in naprej po soteski Predelice do Gorenjega Loga (območje B, sl. 1). Po približno štirih minutah (hitrost čela je bila okrog 15 m/s) je drobirski tok dosegel vas Gorenji Log (odsek C, sl. 1), kjer je v svojih domovih umrlo 7 ljudi, uničenih je bilo 6 hiš, resno poškodovanih pa 23 stanovanjskih ali gospodarskih poslopij ([6], [9] in [10]). Slika 2 prikazuje zračni posnetek opustošenega odseka C, iz katerega je razviden tudi največji doseg opisanega pojava drobirskega toka.

1 DESCRIPTION OF THE DEBRIS-FLOW EVENT

On November 15th, 2000, a landslide glided down the slope of Stože (Fig. 1). The mass mostly stopped at the Mlinč Bridge (Bridge I), just a few percent of the mass came over the bridge (Reach A, Fig. 1). During the next two days the mass was moistened by heavy rain and by the inflow of the Mangart Creek. Just after midnight on November 17th a smaller, additional landslide glided down the slope and triggered the very wet mass of the first landslide into a debris flow. The combined mass swept away the bridge, completely destroying it, and flowed down the narrow canyon of the Predelica Torrent (Reach B, Fig. 1). In about 4 minutes (front velocity about 15 m/s) it reached the village of Gorenji Log (Reach C, Fig.1), where it killed 7 people in their homes, destroyed 6 and severely damaged 23 residential or farm buildings ([6], [9] and [10]). Fig. 2 shows the bottom view of the devastated Reach C, together with the envelope of the debris-flow event.



Sl. 1. *Situacija področja in računski odseki*
Fig. 1. *Situation of the region and the computational reaches*

Sl. 2. *Fotografija območja drobirskega toka v Gorenjem Logu (foto: B. Vlaj, 22. 11. 2000)*
Fig. 2. *Photograph of the debris-flow area in Gorenji Log (photo: B. Vlaj, 22 Nov. 2000)*

Na odseku C pri vasi Gorenji Log je postal tok zaradi dodatnih voda reke Koritnice redkejši in material še bolj razmočen. Po dolini Koritnice je tekel počasneje in deloma odlagal material vzdolž svoje poti. Večina materiala se je odložila navzgor od ožine reke Koritnice na

In Reach C, nearby the village of Gorenji Log, the debris flow received an additional water discharge from the Koritnica River, and it continued its movement more slowly, partly depositing the mass along its path. Most of the debris mass was deposited upstream of the very narrow section of the Koritnica koncu odseka D, manjši del pa je nadaljeval pot proti reki Soči.

Skupaj se je s plazišča Stože premaknilo 1,200.000 m^3 materiala (sl. 1). Prostornina prvega plazu (15. novembra), ki se je ustavil na območju A, je bila ocenjena na približno 600.000 m^3. 17. novembra pa je šlo skozi profil mostu I in naprej po reki navzdol okrog 950.000 m^3 materiala. Od tega ga je približno 800.000 m^3 doseglo vas Gorenji Log, ker se je 150.000 m^3 materiala odložilo vzdolž poti ([6], [9] in [10]).

Creek, at the end of Reach D, and a smaller part of it was transported further down to the Soča River.

In total, a volume of 1.200,000 m^3 was displaced from its original location on the Stože slope (Fig.1). The volume of the first debris-landslide (on November 15th), deposited along Reach A was estimated to be about 600,000 m^3. On November 17th about 950,000 m^3 moved across the section of Bridge I downstream. A volume of about 800,000 m^3 reached the village of Gorenji Log, as 150,000 m^3 were deposited along the path ([6], [9] and [10]).

2 TEORETIČNE OSNOVE MATEMATIČNIH MODELOV

2.1 Izbira modelov

Tok vzdolž odseka A je bil simuliran z modeloma DEBRIF1D in FLO-2D, tok vzdolž odseka B pa je bil tipično enodimenzijski in zato simuliran samo z modelom DEBRIF1D. Na odseku C pri vasi Gorenji Log je bil tok tipično dvodimenzijski in simuliran z obema modeloma, PCFLOW2D in FLO-2D, saj gre za pomembno območje, kjer lahko pride do žrtev in materialne škode. Odsek D je bil simuliran z enodimenzijskim modelom in v zgornjem delu (vas Spodnji Log, sl. 1) tudi z modelom FLO-2D. Za povezavo med zaporednimi odseki so bili uporabljeni izračunani hidrogrami na koncu vzvodnih odsekov.

2.2 Enodimenzijski model DEBRIF1D

Že leta 1972 je bil na Fakulteti za gradbeništvo in geodezijo Univerze v Ljubljani razvit enorazsežen model LAXDAM [18] za simulacijo valov zaradi porušitev pregrad. Kasneje je bil model uporabljen kot osnova za razvoj numeričnega modela SNOWDYN za simulacijo dinamike snežnih plazov ([17] in [16]). Leta 2001 pa je bil model razširjen še za simulacijo drobirskih tokov, DEBRIF1D. Vsi trije modeli rešujejo enodimenzijske St. Venantove enačbe v t.i. “konservativni” obliki.

Glavna razlika med opisanimi pojavi je v formulaciji upora toku ter v začetnih in robnih pogojih. Model DEBRIF1D uporablja izraz za trenjski nagib S_f, ki je vzet iz [14]:

2 THEORETICAL BACKGROUND OF THE MATHEMATICAL MODELS

2.1 The choice of models

The flow along Reach A was simulated using the DEBRIF1D and FLO-2D models, the flow in Reach B was typically one-dimensional and thus simulated only with the DEBRIF1D model. Along Reach C (village of Gorenji Log) the flow was two-dimensional and, as this is the most important region (safety of inhabitants, loss of property), we simulated this reach with both (PCFLOW2D and FLO-2D) models. Reach D was simulated using the one-dimensional model, and along the upper part (village of Spodnji Log, Fig. 1) also with the FLO-2D model. The connections between the subsequent reaches were made with calculated hydrographs at the end of each upstream reach.

2.2 One-dimensional model DEBRIF1D

In 1972 a one-dimensional model, LAXDAM [18], for the simulation of a dam-break flow was developed at the Faculty of Civil and Geodetic Engineering of the University of Ljubljana. Later, this model was used as a basis for developing a numerical model for the simulation of snow avalanche dynamics, SNOWDYN ([17] and [16]). In 2001 this model was extended to a debris-flow model, DEBRIF1D. All three models solve one-dimensional St. Venant equations in what is called the »conservation« form.

The main difference between the three phenomena is in the formulation of the flow resistance and in the formulation of initial and boundary conditions. The DEBRIF1D model uses the formulation for resistance slope S_f, adapted from [14]:

$$S_f = \frac{\tau_y}{\gamma_m \; h} + \frac{K \; V \; \eta}{8 \; \gamma_m \; h^2} + \frac{n_g^2 \; V^2}{h^{4/3}} + S_e + S_b \qquad (1),$$

kjer so: τ_y – mejna strižna trdnost mešanice vode in usedline; γ_m – specifična teža mešanice vode in usedline; h – globina toka; K je brezdimenzijski parameter upora; uporabili smo vrednost $K = 2285$, ki jo priporoča O’Brien [7] za naravne vodotoke z zelo nepravilno razgibanostjo terena; η – dinamična viskoznost mešanice; V – hitrost toka; n_g – Manningov koeficient hrapavosti; S_e – nagib

where: τ_y – the yield shear stress of the sediment-water mixture; γ_m – the specific weight of the water-sediment mixture; h – the flow depth; K is the non-dimensional friction parameter, we used the value of $K = 2285$ that was proposed by O’Brien [7] for natural streams with a highly irregular terrain configuration; η – the dynamic viscosity of the mixture; V – the flow velocity; n_g – the Manning roughness coefficient; S_e

energijskih izgub zaradi vrtincev v hitrih razširitvah, ki so približno enake razliki kinetičnih členov v dveh zaporednih prečnih prerezih [18]; S_b – energijski nagib zaradi ovinkov; uporabljena je bila preprosta enačba, ki je znana iz hidravlike ustaljenega toka [18]:

– the resistance slope due to eddy losses at sharp channel expansions, equal to the difference of the values of the kinetic terms in two subsequent cross-sections [18]; S_b – the resistance slope due to bends; a simple equation, known from steady-state river hydraulics [18] was used:

$$S_b = 2\ \frac{B_b}{r_b\ \Delta x}\ \frac{V^2}{2\ g} \qquad (2),$$

kjer pomenijo: B_b – širino proste gladine v ovinku; r_b – polmer ovinka; Δx – vzdolžno razdaljo med prečnimi prerezi.

Enačba (1) je bila izpeljana iz enačbe za strižno napetost, ki je znana kot kvadratni reološki model:

in which B_b – the free surface width of the bend; r_b – the radius of the bend; Δx – the longitudinal distance between cross sections.

Equation (1) was derived from the equation for shear stress, which is known as the quadratic rheologic model:

$$\tau = \tau_y + \eta\ \frac{dV}{dy} + C\left(\frac{dV}{dy}\right)^2 \qquad (3).$$

V literaturi je enačba (3) znana kot model O´Briena in Juliena, kjer so τ_y – vsota kohezivne strižne napetosti in Mohr-Coulombove napetosti; C – stalnica, y – smer, pravokotno na hitrost toka V.

Za reševanje je uporabljena eksplicitna numerična metoda Lax-Wendroff. Ker je momentna enačba upoštevana v konservativni obliki in rešena s primerno numerično metodo končnih razlik, lahko model delno zajame tudi izgube na čelu vala. To omogoča enoten račun čela s preostalim tokom, brez posebnih tehnik za napredovanje čela [18].

Pomembna lastnost modela DEBRIF1D je, da vključuje izračun začetnega hidrograma $Q(t)$ na nizvodnem koncu začetne drobirske mase. Postopek je vzet iz modela za račun porušnih valov, kjer se v prvem trenutku po porušitvi (t = 0) kota vode in hitrost na mestu pregrade izračuna z dinamično in kontinuitetno enačbe ter enačbo pozitivne karakteristike [18]. Znana mora biti geometrijska oblika plazu pred premikom. V času t > 0 teče račun zvezno od vzvodnega konca plazeče se mase do čela drobirskega toka (premikajoči se rob), hidrogram na pregradnem mestu pa se izračuna posredno. Večina modelov drobirskega toka, med njimi tudi modela PCFLOW2D in FLO-2D, zahteva namreč določitev začetnega hidrograma z uporabo približnih metod in začetne drobirske mase.

In the literature Equation (3) is known as the O´Brien-Julien model, where in τ_y the sum of cohesive yield stress and Mohr-Coulomb's stress is included; C is a constant and y is a direction normal to the flow velocity V.

The explicit, numerical Lax-Wendroff method is used for the solution. Since the momentum equation is used in conservative form and solved by the appropriate finite-difference numerical method, the model can partly take into account the energy losses at the wave front. This enables a direct simulation of the wave front without any special wave-front tracking technique [18].

One important feature of the DEBRIF1D model is that it includes the computation of the initial flow hydrograph $Q(t)$ at the downstream end of the initial debris mass. The procedure is taken from the dam-break flow model, where during the first instant after the dam collapse (t = 0) the water level and the velocity at the dam site are calculated using the momentum and continuity equations and the equation of the forward characteristic [18]. The geometry of the landslide mass before the displacement must be known. At t > 0 the computation runs continuously from the upstream end of the moving landslide mass to the front of the debris flow (moving boundary), and the hydrograph at the "dam site" is calculated implicitly. Most debris-flow models, among them PCFLOW2D and FLO-2D, demand the determination of the initial hydrograph using approximate methods, based on the initial debris mass.

2.3 Dvodimenzijski model PCFLOW2D

Kontinuitetna (4) in enačbi ohranitve gibalne količine (5) in (6), ki opisujejo dvodimenzijski, nestisljiv, globinsko povprečni drobirski tok, so uporabljene v naslednji obliki:

2.3 Two-dimensional model PCFLOW2D

The continuity (4) and momentum Equations (5) and (6), describing two-dimensional, incompressible, unsteady, depth-averaged debris flow, are used in the following form:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \qquad (4)$$

$$\frac{\partial (hu)}{\partial t} + \frac{\partial (hu^2)}{\partial x} + \frac{\partial (huv)}{\partial y} = -gh\frac{\partial h}{\partial x} - gh\frac{\partial z_b}{\partial x} - ghS_{fx} + \frac{\partial}{\partial x}(h\nu_{ef}\frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(h\nu_{ef}\frac{\partial u}{\partial y}) \qquad (5)$$

$$\frac{\partial(hv)}{\partial t}+\frac{\partial(huv)}{\partial x}+\frac{\partial(hv^2)}{\partial y}=-gh\frac{\partial h}{\partial y}-gh\frac{\partial z_b}{\partial y}-ghS_{fy}+\frac{\partial}{\partial x}(h\nu_{ef}\frac{\partial v}{\partial x})+\frac{\partial}{\partial y}(h\nu_{ef}\frac{\partial v}{\partial y}) \quad (6),$$

kjer so: t – čas; h – globina toka; u in v – globinsko povprečni komponenti hitrosti v smereh x in y; z_b – kota dna, g – gravitacijska stalnica in ν_{ef} – koeficient efektivne viskoznosti. Člena S_{fx} in S_{fy} izražata nagib energijske črte v smereh x in y in se lahko analogno kakor pri formulaciji za enorazsežen tok (1) zapišeta v naslednji obliki:

where: t – the time; h – the flow depth; u and v – the depth-averaged velocity components in the x and y directions; z_b – the bottom level; g – the gravity constant and ν_{ef} – the effective coefficient of viscosity. The terms S_{fx} and S_{fy} express energy-line slopes in the x and y directions and can be analogous to the one-dimensional flow formulation (Eq. 1) written as follows:

$$S_{fx}=\frac{\tau_y}{\gamma_m\ h}+\frac{K\ u\ \eta}{8\ \gamma_m\ h^2}+\frac{n_g^2\ u\ \sqrt{u^2+v^2}}{h^{4/3}} \quad (7)$$

$$S_{fy}=\frac{\tau_y}{\gamma_m\ h}+\frac{K\ v\ \eta}{8\ \gamma_m\ h^2}+\frac{n_g^2\ v\ \sqrt{u^2+v^2}}{h^{4/3}} \quad (8).$$

Sistem povezanih parcialnih diferencialnih enačb (4) do (6) je rešen z numerično metodo končnih prostornin [15]. Glavne značilnosti metode so premaknjena numerična mreža, kombinacija vzvodne in centralno diferenčne sheme (t.i. hibridna shema) ter iterativni postopek popravkov globin (SIMPLE). Za integracijo po času je uporabljena polna implicitna shema, ki zagotavlja stabilno in dovolj točno rešitev tudi pri razmeroma visokih Courantovih številih (do 10). Simulirati je mogoče tako mirne kakor tudi deroče tokove [5].

Za račune drobirskega toka v Logu pod Mangartom je bila upoštevana enakomerna numerična mreža s korakoma $\Delta x = \Delta y = 2$ m, zajeti pa so bili tudi vsi objekti na obravnavanem računskem področju.

The set of coupled partial differential equations (4) to (6) is solved by the finite-volume numerical method [15]. The main characteristics of the method are a staggered numerical grid, the combination of an upwind and central-difference schemes (the so-called hybrid scheme) and an iterative procedure of depth corrections (SIMPLE). A fully implicit scheme is used for time integration providing a stable and accurate solution even at relatively high Courant numbers (up to about 10). It is possible to simulate both subcritical or supercritical flows [5].

For the computations of the debris flow at Log pod Mangartom, the uniform mesh $\Delta x = \Delta y = 2$ m was used and all buildings in the computational domain were also taken into account.

2.4 Dvodimenzijski model FLO-2D

To je tržni dvodimenzijski model, ki temelji na metodi končnih razlik in je bil razvit v ZDA [7]. Model je bil narejen za račun razširjanja nenewtonskih poplavnih valov, blatnih in drobirskih tokov. V ZDA ga za uporabo priporoča Zvezna uprava nezgod (Federal Emergency Management Agency - FEMA), široko pa se uporablja tudi v Avstriji, Švici in Italiji. Dvodimenzijske kontinuitetna in dinamični enačbi so podobne enačbam (4) do (6), edina razlika je, da so uporabljene v nekonservativni obliki. Reološki členi so ovrednoteni na podlagi prvih treh členov v enačbi (1), po katerih dobimo dvodimenzijski enačbi (7) in (8). Na računskem področju Loga pod Mangartom je bila upoštevana enakomerna numerična mreža velikosti $\Delta x = \Delta y = 4$ m.

Ker je bil model že uspešno uporabljen za simulacije različnih praktičnih primerov drobirskega toka [8], smo ga uporabili hkrati z našim modelom PCFLOW2D, da bi dobili bolj zanesljive rezultate. Kakor bo prikazano pri umerjanju, je bilo ujemanje med rezultati obeh modelov dovolj dobro.

2.4 Two-dimensional model FLO-2D

This is a commercial, two-dimensional, finite-difference model, developed in the USA [7]. The model was conceived for routing non-Newtonian flood flows, as well as mudflows and debris flows. In the USA it is recommended for use by the Federal Emergency Management Agency (FEMA), and it is also widely used in Austria, Switzerland and Italy. The two-dimensional continuity and momentum equations are similar to Eqs. (4) to (6), the only difference is that they are used in a non-conservative form. The rheological terms are evaluated as the first three terms in Eq. (1) resulting in the two-dimensional Eqs. (7) and (8). The uniform mesh $\Delta x = \Delta y = 4$ m was taken into account for the computational domain at the village of Log pod Mangartom.

As the model has been successfully used for several practical cases of debris-flow simulations [8], we used this model in parallel with our PCFLOW2D model to get more reliable results. As we showed in the calibration process, we obtained a reasonable agreement between the results of both models.

3 UMERJANJE MATEMATIČNIH MODELOV

Pri umerjanju eno- in dvodimenzijskih modelov smo iskali ustrezne vrednosti treh reoloških parametrov v enačbah (1), (7) in (8): τ_y, η in n_g. Uporabili smo tri metode za določitev teh vrednosti: (a) razpoložljive vrednosti iz literature; (b) rezultate geomehanskih laboratorijskih preizkusov [9]; in (c) vrednosti, dobljene z umerjanjem modela na temelju primerjave s terenskimi meritvami.

Prvi plaz na odseku A (15. novembra 2000) je bil razmeroma suh in se je ustavil na pobočju z nagibom 16 %. Enorazsežen model je ta pojav simuliral z vrednostmi τ_y = 2000 N/m^2 in η = 156 Pa.s. Zelo moker drobirski tok vzdolž odseka B (17. novembra 2000) je bil umerjen pri vrednostih τ_y = 20 N/m^2 in η = 40 Pa.s. Ker obsega odsek B zelo strm, ozek kanjon s povprečnim padcem 17 % in največjim padcem 119 %, se je Manningov koeficient spreminjal v zelo širokih mejah od 0,03 do 0,35 sm$^{-1/3}$. Največje vrednosti so bile umerjene na najstrmejših delih odseka B, kjer je moral biti tok podoben vodnemu slapu. Slika 3 prikazuje ovojnico simuliranih najvišjih kot in na podlagi največjega dosega zabeležene gladine drobirskega toka vzdolž zgornjega dela odseka B. Menimo, da je ujemanje glede na zapletenost pojava zadovoljivo.

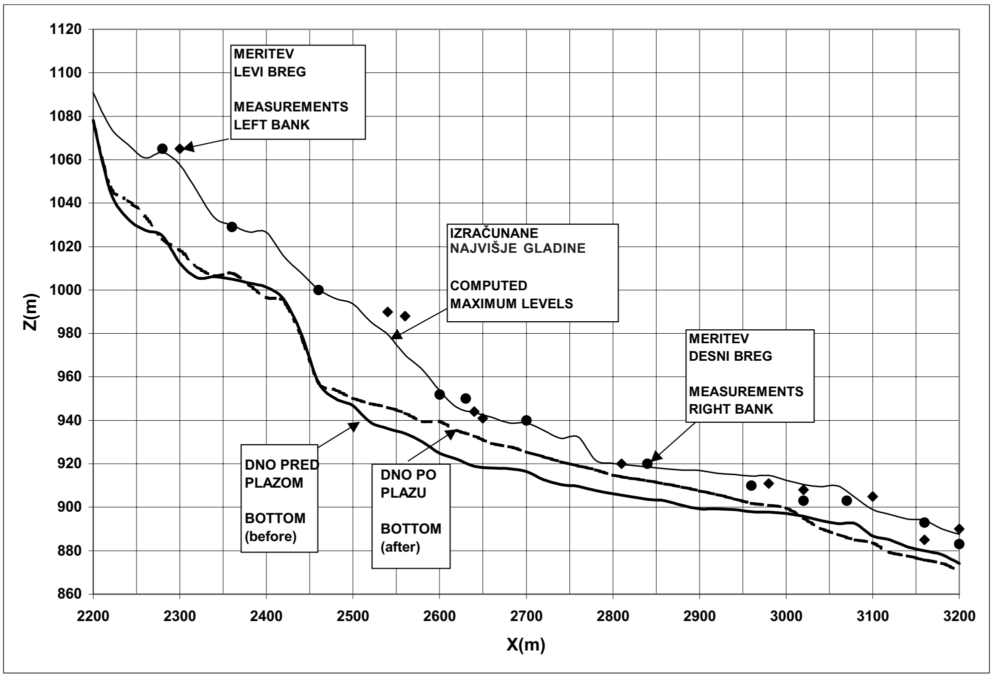
Podobna točnost je bila dobljena tudi na odsekih A, C in D. Za odsek C je primerjava merjenega in z dvodimenzijskima modeloma PCFLOW2D in FLO-2D simuliranega dosega drobirskega toka prikazana na sliki 4. Umerjene

3 CALIBRATION OF THE MATHEMATICAL MODELS

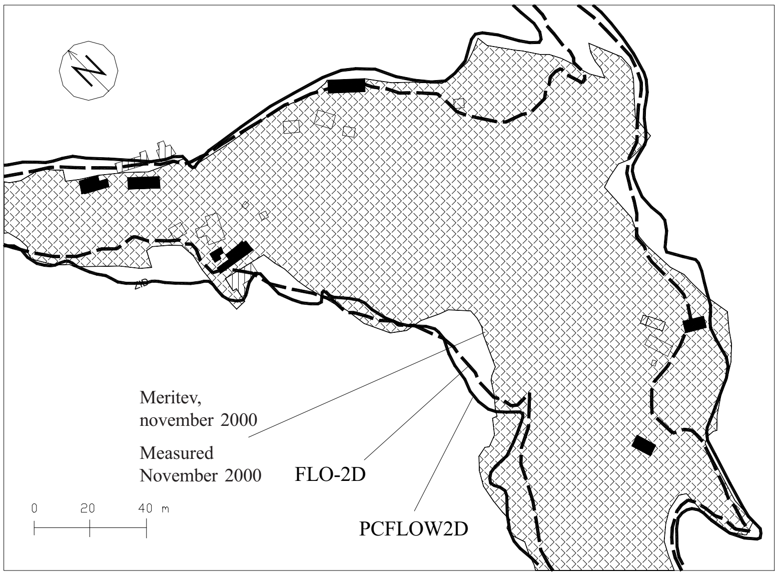
Calibration of both the one- and two-dimensional models was made by finding proper values of the three rheological parameters in Eqs. (1), (7) and (8): τ_y, η, and n_g. We used three possible methods for determining these values: (a) values available in the literature; (b) results of geo-mechanical laboratory measurements [9]; and (c) values obtained by the calibration of the model – comparison with the field measurements.

The first landslide along Reach A (November 15th, 2000) was relatively dry and it stopped on a slope of 16%. The one-dimensional model simulated this phenomenon with values of τ_y = 2 000 N/m^2, and η = 156 Pa.s. The very wet debris flow along Reach B (November 17th, 2000) was calibrated with the values τ_y = 20 N/m^2 and η = 40 Pa.s. Since Reach B is a very steep, narrow canyon, with an average slope of 17 %, and a maximum slope of 119 %, the Manning coefficient changed in broad limits from 0.03 to 0.35 sm$^{-1/3}$. The greatest values were found along the steepest parts of Reach B, where the flow must have been similar to a waterfall. Fig. 3 shows the longitudinal profile of the simulated and measured maximum debris-flow surface elevations along the upper part of Reach B. We can consider the agreement as satisfactory.

Similar accuracy was also obtained for Reaches A, C and D. Along Reach C, the comparison of the measured and simulated inundation limits obtained by the two-dimensional models PCFLOW2D and FLO-2D is shown in Fig. 4. The calibrated debris-



Sl. 3. *Primerjava merjenih in izračunanih kot drobirskega toka vzdolž zgornjega dela odseka B*
Fig. 3. *Comparison of measured and computed debris-flow elevations along the upstream part of Reach B*



Sl. 4. *Primerjava merjenega in izračunanega območja dosega drobirskega toka vzdolž odseka C*
Fig. 4. *Comparison of measured and computed inundation limits of the debris flow along Reach C*

vrednosti drobirskega toka na odseku C so bile $\tau_y = 20$ N/m^2, $\eta = 10$ Pa.s in $n_g = 0{,}05$ do $0{,}065$ sm$^{-1/3}$. Medsebojna primerjava izračunanih najvišjih gladin modelov PCFLOW2D in FLO-2D ter primerjava z najvišjimi kotami drobirskega toka, zabeleženimi na podlagi sledov dosega drobirskega toka z dne 17. novembra 2000 (primer a, slika 5) je pokazala, da lahko točnost modelov na odseku C ocenimo na ±1,5 m za najvišje kote v osi strug Predelice in Koritnice ([2] do [4]).

flow values along Reach C were $\tau_y = 20$ N/m^2, $\eta = 10$ Pa.s and $n_g = 0.05$ to 0.065 sm$^{-1/3}$. The comparison of the maximum debris-flow elevations computed by the PCFLOW2D and FLO-2D models, as well as the comparison with the measured elevations obtained by the inundation limits on November 17th, 2000 (Case a, Fig. 5), has demonstrated that the accuracy of both models. On Reach C, it can be estimated to ±1.5 m for the maximum elevations along the axes of the Predelica and Koritnica Creeks ([2] to [4]).

4 RAČUNSKI REZULTATI

4.1 Določitev primerov za simulacijo

Na podlagi podrobnih geoloških, hidroloških in geomehanskih analiz je bilo ugotovljeno, da so nad odlomnim robom plazu v Stožah še vedno obstoječe nestabilne mase, tako da obstaja možna nevarnost novih plazov enakega ali celo večjega obsega kakor novembra 2000 ([6], [9] in [10]). Med strokovnjaki je prevladalo enotno mnenje, da bi morala biti vas varovana proti plazovom enakega reda velikosti kakor v novembru 2000, ko se je premaknilo 1,200.000 m^3 materiala. Pri dejanskem plazu se je okrog 400.000 m^3 odložilo vzdolž odsekov A in B, v prihodnje pa je moč pričakovati odlaganje samo 200.000 m^3. Dno struge je namreč deloma zapolnjeno z materialom prejšnjih plazov, tako da bi bila prostornina materiala, ki bi dosegel vas, 1,000.000 m^3. Za oceno možne nevarnosti so bile narejene še druge simulacije z naslednjimi možnimi začetnimi prostorninami materiala: 2,000.000 m^3, 1,600.000 m^3 in 800.000 m^3. Narejenih je bilo tudi več simulacij, pri katerih je bila začetna prostornina zmanjšana za 600.000 m^3. Toliko namreč približno znaša zadrževalna prostornina štirih pregrad. Slika 5 prikazuje hidrograme drobirskega toka pri mostu II v Gorenjem

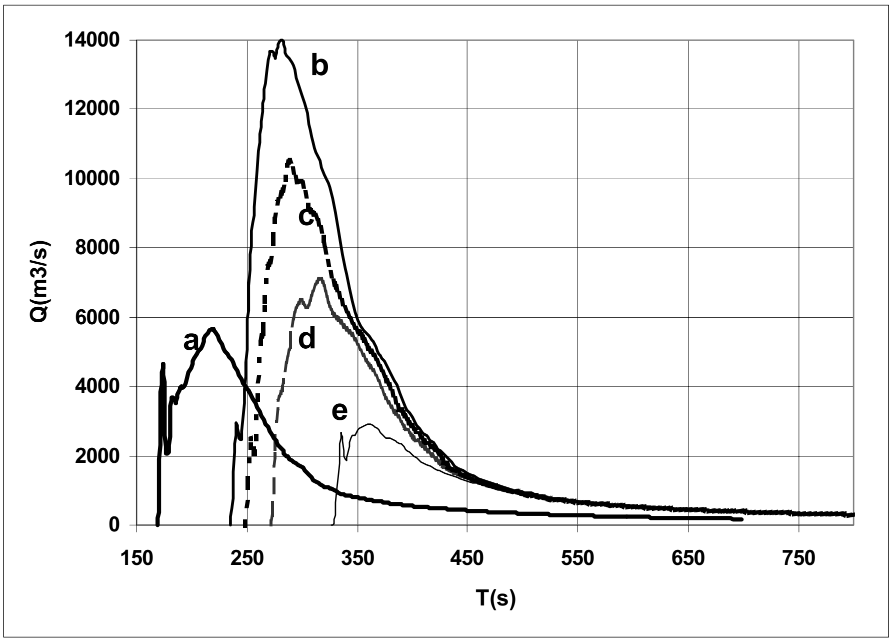
4 COMPUTATIONAL RESULTS

4.1 Determination of cases for simulation

Based on detailed geological, hydrological, and geo-mechanical analyses, it was determined that above the region of the last landslide on the Stože slope there are potentially unstable masses and that in the future there is a potential danger of further landslides of the same or even greater magnitude as that in November 2000 ([6], [9] and [10]). Among professionals it was agreed that the village should be protected against the same magnitude of landslide mass as that of November 2000, when the total displaced volume was 1.200,000 m^3. In the original landslide about 400,000 m^3 were deposited along Reaches A and B, while in the future only a deposition of 200,000 m^3 can be expected, as the bed is partially filled with the material of previous landslides, and thus a volume of 1.000,000 m^3 would reach the village. To estimate the potential danger, other simulations were also made for possible initial volumes of 2.000,000 m^3, 1.600,000 m^3, and 800,000 m^3. A series of simulations has also been made with the initial volumes reduced for 600,000 m^3. This would be approximately the retention volume of four dams. Fig. 5 shows debris-flow hydrographs at the site of Bridge II for the event of November 17th, 2000, and for

Logu za dogodek 17. novembra 2000 in štiri primere mogočih plazov oz. drobirskih tokov, ki so bili dobljeni z modelom DEBRIF1D. Čas $T = 0$ s pomeni trenutek sprožitve drobirskega toka na plazišču v Stožah, razen v primeru ponovitve dogodka, dne 17. novembra 2000, ko $T = 0$ pomeni čas sprožitve toka pri mostu I v Mlinču. Izračunani hidrogrami so bili temelj za simulacije drobirskega toka vzdolž odsekov C in D.

four cases of potential future landslide/debris flows, as simulated by the DEBRIF1D model. Time T = 0 s is the moment when the debris flow starts to move from the Stože slope, except for the case of November 17th, 2000, where T = 0 s means the time when the debris flow started to move at the Bridge I in Mlinč. Computed hydrographs were the basis for all the simulations of the debris flow along the downstream reaches C and D.



Sl. 5. *Izračunani hidrogrami pretokov drobirskega toka pri mostu II v Gorenjem Logu. Krivulje ustrezajo naslednjim drobirskim prostorninam a: $V = 0,8 * 10^6$ m^3 (dejanski dogodek 17. novembra 2000); b: $V = 1,8 * 10^6$ m^3 ; c: $V = 1,4 * 10^6$ m^3 ; d: $V = 1,0 * 10^6$ m^3 ; e: $V = 0,6 * 10^6$ m^3.*

Fig. 5. *Computed hydrographs of the debris-flow discharge at Bridge II in Gorenji Log. Curves correspond to debris volumes: a: $V = 0.8 * 10^6$ m^3 (real event on November 17th, 2000); b: $V = 1.8 * 10^6$ m^3 ; c: $V = 1.4 * 10^6$ m^3 ; d: $V = 1.0 * 10^6$ m^3 ; e: $V = 0.6 * 10^6$ m^3.*

4.2 Rezultati in razprava

Za primer, ko bi vas doseglo 1,000.000 m^3 drobirja, so na slikah 6 in 7 prikazani izračunani vektorji hitrosti in prosta gladina drobirskega toka vzdolž odseka C 70 sekund po prehodu čela vala skozi prečni profil mostu II v Gorenjem Logu. Oba rezultata sta bila dobljena z dvodimenzijskim modelom PCFLOW2D za primer, ko bi bil odložen material prejšnjih drobirskih tokov iz dna struge Predelice vzdolž odseka C v glavnem že odstranjen.

Za oceno obstoječe nevarnosti so bile narejene še simulacije z drugimi možnimi prostorninami, opisanimi v poglavju 4.1. Upoštevanih je bilo tudi več različic ureditve strug Predelice in Koritnice vzdolž odsekov C in D, da bi določili cenovno najugodnejšo možnost varovanja obeh vasi. Rezultati teh simulacij so podani v poročilih [2], [3] in [4], kjer so podrobno navedeni tudi končno predlagani ukrepi varovanja vasi Log pod Mangartom. Najbolj učinkoviti in cenovno sprejemljivi ukrepi so: odstranitev nasutega

4.2 Results and discussion

For the case when 1.000,000 m^3 of the debris volume would reach the village, Figs. 6 and 7 show the computed velocity vectors and the free surface of the debris flow along Reach C 70 seconds after the transition of the wave front through the cross-section of Bridge II. Both results were obtained by the two-dimensional model PCFLOW2D for the situation when the old debris material from the bed of Predelica along Reach C had been mainly removed.

To estimate the potential danger, other simulations were also made for the possible initial volumes described in section 4.1. Several variations of the riverbed training measures along the Predelica and Koritnica Creeks at Reaches C and D were taken into account in the simulations, to determine the most cost-effective solution to protect both villages. The results of these computations can be found in the reports [2], [3] and [4], where a detailed description of the measures to protect Log pod Mangartom village is also given. The most effective and economic measures are the materiala prejšnjih drobirskih tokov iz struge Predelice vzdolž odseka C, razširitev ozkega dela doline pri mostu II v Gorenjem Logu ter izgradnja vzdolžnih zidov višine do 2 m ob naseljih Gorenji in Spodnji Log.

Za model PCFLOW2D je bila narejena tudi analiza občutljivosti rezultatov za spremembo gostote numerične mreže in iztočnega robnega pogoja [6]. Pri redkejši numerični mreži velikosti 4 x 4 m so se rezultati v primerjavi z mrežo 2 x 2 m, ki je bila uporabljena pri končnih izračunih, le malo spremenili. Različni robni pogoj na iztoku (kritični tok ali ničelni gradienti hitrosti in globin v smeri iztoka) pa je na izračunane gladine vplival krajevno, vendar ne dlje kakor okoli 80 m navzgor od iztoka.

Omenimo še, da v modelih erozija in odlaganje drobirskega materiala niso bili zajeti neposredno z enačbami, temveč posredno. Na mestih očitne erozije so bili tako pri umerjanju kakor pri končnih računih upoštevani profili, izmerjeni po prehodu drobirskega toka. Odlaganje na vzvodnih odsekih je bilo navzdol po reki upoštevano tako, da je bil pri vtočnem hidrogramu $Q - t$ odrezan zadnji, padajoči del hidrograma, katerega prostornina je ustrezala odloženemu materialu.

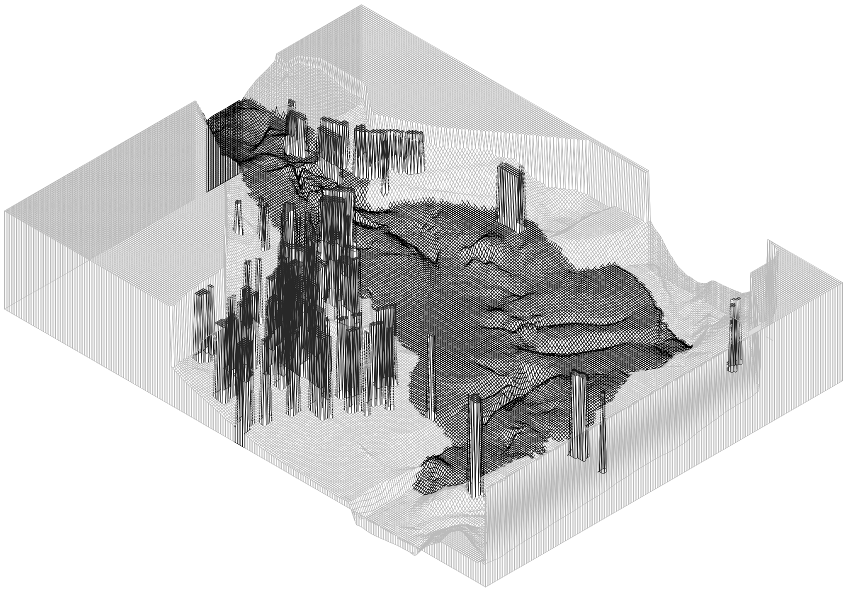
removal of the deposited debris material from the bed of the Predelica Creek along Reach C, the enlargement of the narrow part of the valley at Bridge II in Gorenji Log and the construction of longitudinal walls up to 2 m high along the villages of Gorenji and Spodnji Log.

For the model PCFLOW2D, the sensitivity analysis for different mesh sizes and outflow boundary conditions was also made [6]. For the coarser grid of 4 x 4 m the results did not change significantly in comparison with the mesh of 2 x 2 m, which was used in the final computations. Different outflow boundary conditions (critical flow or zero velocity and depth gradients in the direction of the outflow) influenced debris-flow elevations locally up to about 80-m upstream from the outflow cross-section.

It is worth mentioning that the erosion and deposition of the debris material were not simulated directly by the equations, but they were taken into account indirectly. At the places where the erosion was obvious, the cross-sections that had been measured after the transition of the debris flow were considered during the calibration process and final computations. The deposition at upstream sections was taken into account downstream by cutting off the falling part of the inflow hydrographs that corresponded to the volume of the deposited material.

Sl. 6. *Izračunani vektorji hitrosti vzdolž odseka C 70 sekund po prehodu čela vala skozi prečni profil mostu II v Gorenjem Logu*

Fig. 6. *Computed velocity vectors along Reach C 70 seconds after the transition of the wave front through the cross-section of Bridge II in Gorenji Log*



Sl. 7. *3D pogled na izračunano gladino drobirskega toka na odseku C 70 sekund po prehodu čela vala skozi prečni profil mostu II v Gorenjem Logu*
Fig. 7. *3D view of the computed debris-flow surface along Reach C 70 seconds after the transition of the wave front through the cross-section of Bridge II in Gorenji Log*

5 SKLEPI

Končni cilji matematičnega modeliranja gibanja drobirskega toka so zapleteni: poleg varovanja vasi Log pod Mangartom pred mogočimi prihodnjimi drobirskimi tokovi mora biti zagotovljena tudi poplavna varnost. Končna ureditev strug Predelice in Koritnice ter okoliškega terena mora biti optimizirana še z ekonomskega in okoljskega vidika. Pomembni so tudi socialni vidiki, predvsem mora biti upoštevano mnenje vaščanov, ki jih pojav drobirskega toka ogroža.

V primeru drobirskega toka pod plaziščem Stože se je kombinacija enodimenzijskega modela DEBRIF1D in dveh dvodimenzijskih modelov PCFLOW2D in FLO-2D pokazala kot pravilna metodologija za simulacijo prihodnjih podobnih nesreč in načrtovanja ukrepov varovanja vasi Log pod Mangartom. Overitev vseh treh modelov je potrdila, da je zanesljivost modelnih rezultatov zadovoljiva. Kvadratni zakon upora drobirskega toka, ki ga je predlagal O'Brien [14], je dala sprejemljive rezultate tudi za primer daljših odsekov, kjer se režim toka spreminja. FLO-2D je pokazal določeno glajenje izračunanih kot v primerjavi z modelom PCFLOW2D, v povprečju pa je ujemanje rezultatov obeh modelov sprejemljivo, natančnost pa primerljiva.

5 CONCLUSIONS

The final goal of the mathematical modelling of debris flow is complex: besides protection against possible future debris flow in the village of Log pod Mangartom, protection against high water floods also has to be ensured. The final arrangement of the Predelica and Koritnica riverbeds and the nearby terrain has to be optimized from the economic and from the environmental points of view. Also the social aspects – the opinions of the local villagers, who are affected by the danger – have to be taken into account.

In the case of the debris flow below Stože, the combination of the one-dimensional model DEBRIF1D and the two two-dimensional models PCFLOW2D and FLO-2D proved to be the right methodology for the simulations of possible future disastrous events and to design measures to protect the village of Log pod Mangartom. The verification of the three models has proved the satisfactory reliability of the model results. The quadratic law of debris-flow resistance, proposed by O'Brien [14], gives acceptable results, even for flows along longer reaches, where the flow regimes change. FLO-2D shows a certain smoothing of the computed levels in comparison with PCFLOW2D, but on average the agreement of the results of both models is acceptable and the accuracy is comparable.

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