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LABORATORIJSKA UPORABA SLEDILA ZA MERJENJE DINAMIKE PREMEŠČANJA PLAVIN V TURBULENTNIH TOKOVIH
LABORATORY APPLICATION OF A SATELLITE FOR MEASURING DYNAMICS OF SEDIMENT TRANSPORT IN TURBULENT FLOWS

Matjaž MIKOŠ, Mojca SPAZZAPAN

Za sodobne študije premeščanja rečnih sedimentov smo razvili in testirali novo instrumentizirano umetno sledilo (satelit), imenovano prodnik vohun (SPY), kjer kratica v angleščini pomeni "dinamiko posameznih delcev". Ta nova vrsta sledila ima vgrajena tipala v umetni intrumentizirani kroglasti prodnik premera 99 mm in mase 994,6 g. Sledilo se lahko uporablja za prepoznavanje in merjenje različnih kinematičnih in dinamičnih elementov (predvsem trčnih in trenjskih sil) v času gibanja po rečnem dnu ali v času mirovanja na rečnem dnu. Satelit je bil testiran v laboratorijskih pogojih v žlebu s tremi različnimi vrstami dna žleba (dno iz nevezanih prodnikov, jekleno dno, dno iz betonskih plošč z vgrajenimi prodniki) in različnim naklonom dna žleba med 0,025 in 0,055. Glavni merjeni dinamični parametri so bile amplitude trčnih in trenjskih sil ter čas med posameznimi kontakti sledila. Dobljeni rezultati za brezdimenzijske strižne napetosti od 0,05 do 0,12 so pokazali na uporabno vrednost satelita v laboratorijskih pogojih za raziskovanje premeščanja posameznih sedimentnih delcev v turbulentnih tokovih.
Ključne besede: *premeščanje plavin, rečna hidravlika, merilni instrumenti, sledila, laboratorijski poskusi, pospeškometri*

We have developed and tested a new instrumented artificial satellite for advanced sediment transport studies, called SPY-Cobble, where the acronym SPY stands for "Single Particle dYnamics". This new type of tracers with internal sensors is an artificial, instrumented spherical cobble of 99 mm in diameter and has a mass of 0.9946 kg. It may be used for detection and measurements of different elements of kinematics and dynamics (especially contact forces due to impact and friction) when moving as bed load or resting on the bed surface. The satellite was tested under controlled laboratory conditions in a flume using three different flume bed materials (loose sediment bed made of cobble and boulder clasts, steel bed, flume bed made of concrete plates with cast pebble clasts) and different flume slopes between 0.025 and 0.055. The main measured dynamic parameters were the amplitudes of impact and friction forces and the time between contacts of the tracer. The obtained results for non-dimensional shear stress between 0.05 and 0.12 have shown the applicability of the satellite within the laboratory environment for transport studies on single sediment particle movement in turbulent flows.
Key words: *sediment transport, fluvial hydraulics, measuring instruments, tracers, laboratory experiments, accelerometers*

1. UVOD

Merilno napravo, razvito za spremljanje dinamike premeščanja grobih plavin, smo poimenovali prodnik vohun. Razvoj in testiranje prodnika vohuna sta opisana drugje (Spazzapan *et al*., 2004).

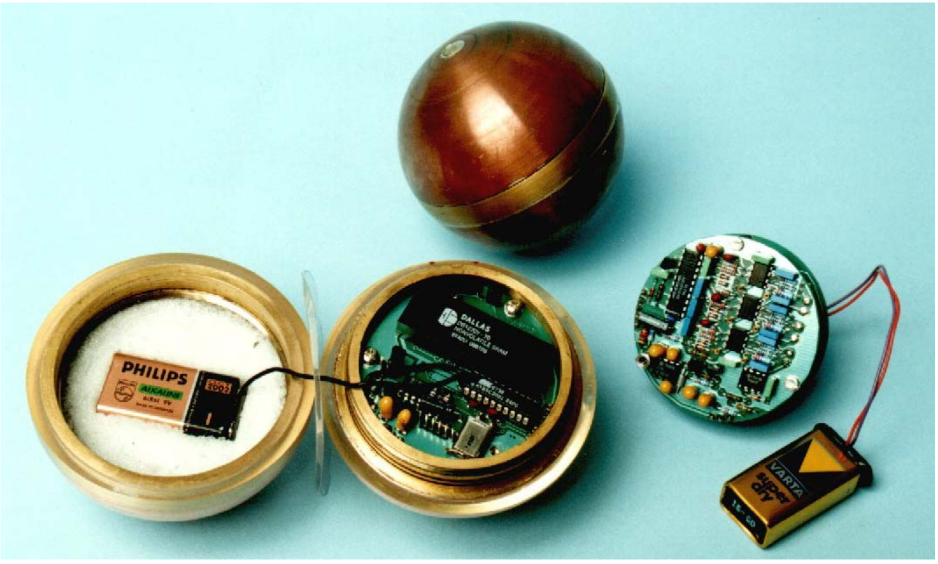
Do današnje oblike je prototip prešel skozi več razvojnih obdobij. V sedanji obliki je

1. INTRODUCTION

The measuring device developed for following dynamics of coarse sediment transport was called the SPY-Cobble. The development and testing of the satellite are described elsewhere (Spazzapan *et al*., 2004).

Up to its present form, the prototype has undergone several phases of development. At sledilo sestavljeno iz kroglaste kovinske konstrukcije, oblečene v epoksidno zaščitno plast, dveh elektronskih tiskanin, ki sta nameščeni vzporedno v njegovem središču, zamenljivega vira energije (9 V baterija), vgrajenega v eni polovici kovinske kroglaste konstrukcije, in 3 enoosnih pospeškometrov, pritrjenih na kovinsko konstrukcijo na drugi strani (slika 1). Prodnik vohun je v taki izvedbi 99 mm velika krogla z maso 994,6 g. Metoda in izvedba naprave je v Sloveniji patentirana (Mikoš *et al.*, 2001), oboje je tudi v svetovnih razmerah patentibilno.

present, the satellite consists of a spherical metal construction coated by epoxy resin, two built-in electronic boards, which are mounted horizontally in its centre, a replaceable power source, which is a standard 9V battery, built-in on one side of the metal construction, and three one-axis accelerometers attached to the metal construction on the other side (see Figure 1). The SPY-Cobble in this composition is 99 mm in diameter and has a mass of 994.6 g. The method and the apparatus are patented in Slovenia (Mikoš *et al.*, 2001) and are patentable worldwide.



Slika 1. Prodnik vohun in njegovi sestavni deli. Zaprta medeninasta krogla brez epoksidne zaščitne plasti (zgoraj) in elektronski tiskanini in vir napajanja (desno).
Figure 1. SPY-Cobble and its parts. The closed brass sphere with no epoxy coating (on top) and the two electronic boards and a battery (on right).

2. REZULTATI MERITEV

Merilno napravo z dodanim pasivnim radijskim oddajnikom bi lahko uporabljali tudi v naravnem rečnem okolju. Vendar smo jo tako, kot je, uporabili samo v laboratorijskih pogojih. Najprej smo testirali njeno uporabnost na zraku in pod vodo v laboratorijskem žlebu na Fakulteti za gradbeništvo in geodezijo Univerze v Ljubljani. Ti rezultati so prikazani drugje (Mikoš *et al.*, 2000). Nato smo sistematično opravili dva niza laboratorijskih meritev v nagibnem laboratorijskem žlebu na Svobodni univerzi v Berlinu (Freie Universität Berlin).

2. MEASUREMENT RESULTS

The device with an added passive radio transmitter could be used also in the natural river environment. But we have used the device such as it is under laboratory conditions only. Firstly, it has been tested in air and under water in a laboratory flume at the Faculty of Civil and Geodetic Engineering in Ljubljana. Results of these measurements are presented elsewhere (Mikoš *et al.*, 2000). Secondly, we have systematically conducted two sets of measurements in a tilting laboratory flume at the Free University in Berlin.

2.1 PRVI NIZ LABORATORIJSKIH POSKUSOV

Prvi niz sistematičnih laboratorijskih poskusov smo opravili v 10 m dolgem in 0,81 m širokem nagibnem laboratorijskem žlebu na Svobodni univerzi v Berlinu. Dno žleba je bilo prekrito z gibljivimi naravnimi prodniki s srednjim zrnom d_m = 86 mm in d_{90} = 93 mm (prodniki so bili sicer v intervalu od 20 do 120 mm). Opravili smo 9 poskusov, kjer je vsak poskus obsegal vsaj 10 posameznih meritev. Med vsako meritvijo smo merili različne parametre toka, prikazane v preglednici 1. Premer prodnika vohuna je bil D = 0,099 m, gostota je bila 1957,7 kg/m^3 in relativna gostota z ozirom na vodo je bila s = 1,9577.

Srednjo pretočno hitrost v žlebu smo merili z robustnim elektromagnetnim merilcem pretoka (Nautilus, merilno območje 0–2,5 m/s), meritev smo povprečili na 5 s. Merili smo tudi povprečno globino toka ter s pomočjo povprečne hitrosti toka ocenili dejanski pretok vode v žlebu. Na osnovi enačb stalnega enakomernega toka smo izračunali različne količnike (k_{St} in c) kakor tudi Froudovo število Fr, ki je pokazalo, da je bil tok tako v mirnem kot tudi v deročem režimu. Na začetku vsake posamezne meritve smo prodnik vohun položili v vodni tok na zgornjem koncu žleba. Tok je prodnik odnesel preko hrapavega dna žleba do konca v nekaj 10 s. Izbrana je bila dolžina meritve 10 s (zaradi relativno počasnega prenosa podatkov iz prodnika v računalnik).

Razvili smo postopek za analizo izmerjenega signala, pri čemer smo upoštevali samo izmerjene pospeške, večje od 0,05 g. Vsak tak kratek niz pospeškov smo imenovali dogodek. Minimalni in maksimalni časovni razmik med posameznimi dogodki je bil pri analizi nastavljen na 25 ms in 2 s. Spodnja meja 25 ms pomeni, da so bili izmerjeni pospeški, večji od 0,05 g, ki so si sledili v zaporedju krajšem od 25 ms, prepoznani kot en dogodek. Prepoznani dogodki v izmerjenem signalu so bili sešteti za vsako posamezno meritev in vsak poskus (preglednica 1).

2.1 FIRST SET OF LABORATORY TESTS

We systematically conducted the first set of laboratory tests in a 10-m long and 0.81-m wide tilting laboratory flume at the Free University in Berlin. Its bottom was covered with movable natural clasts with the arithmetic mean d_m = 86 mm and d_{90} = 93 mm, respectively (clasts were in the range between 20 mm and 120 mm). We performed 9 tests each comprising at least 10 separate runs. During each run, various flow parameters were measured, as presented in Table 1. The diameter of the SPY-Cobble was D = 0.099 m, density was 1957.7 kg/m^3, and relative density to water was s = 1.9577.

The mean water velocity was measured by a robust electromagnetic flow sensor (Nautilus, measuring range from 0 m/s to 2.5 m/s), averaging over 5 seconds. The water depth was gauged, and using mean flow velocities the actual water discharge was determined. On the basis of equations for steady uniform flow, different coefficients (k_{St} and c) were calculated as well as the Froude number Fr, which shows that the flow was sub- as well as supercritical. At the beginning of each run, the SPY-Cobble was introduced into the upper end of the flume and was transported by the flow over the rough bed for several tens of second. The measurement during each run was set to be 10 seconds long (due to the relatively slow data transfer from the device to a computer).

An algorithm was developed for processing of the measured signal, taking into account only the measured accelerations larger than 0.05 g. Each such short set of accelerations was then called an event. The minimal and maximal time span between events was for the analysis set to be 25 ms and 2 s, respectively. The lower limit of 25 ms means that the measured accelerations larger than 0.05 g in a sequence shorter than 0.25 ms were recognised as one event. Recognised events in the measured signal were counted for each run and test (see Table 1).

Preglednica 1. Pregled prvega niza laboratorijskih poskusov v nagibnem žlebu.
Merjeni parametri toka: S – nagib dna, h – pretočna globina, v – srednja pretočna hitrost; računani parametri toka: Q – pretok, Fr – Froudovo število, k_{St} – Stricklerjev koeficient, c – Chezyjev parameter, $\theta = (S\,h) / ((s-1)\,D)$ – brezdimenzijska strižna napetost (Shieldsov parameter); analizirani parametri: F – srednja maksimalna sila, t – srednji časovni zamik.
Table 1. On overview of the first set of laboratory tests in the tilting flume. Measured flow parameters: S – bottom slope, h – water depth, v – mean flow velocity; calculated flow parameters: Q – water discharge, Fr – Froude number, k_{St} – Strickler's coefficient, c – Chezy parameter, $\theta = (S\,h) / ((s-1)\,D)$ – non-dimensional shear stress (Shields parameter); analysed parameters: F – mean peak force, t – mean time lag.

			meritve – *Measured*			račun – *Calculated*					analiza – *Analysed*	
poskus *Test*	meritev *Runs* [-]	dogodki *Events* [-]	S [-]	h [cm]	v [m/s]	Q [l/s]	Fr [-]	k_{St} [$m^{1/3}$/s]	c [-]	θ [-]	F [N]	t [s]
1	11	545	0.035	19.0	1.37	211	1.01	22.16	5.36	0.070	17.13	0.183
2	11	571	0.040	18.5	1.39	208	1.05	21.25	5.19	0.078	16.93	0.191
3	11	522	0.045	18.0	1.43	208	1.16	21.15	5.07	0.085	23.03	0.187
4	11	512	0.055	17.0	1.47	202	1.30	20.43	4.85	0.099	26.22	0.187
5	11	451	0.025	26.0	1.38	291	0.75	21.43	5.46	0.069	14.68	0.172
6	10	383	0.030	25.0	1.44	292	0.85	20.95	5.31	0.079	20.84	0.217
7	10	470	0.035	24.0	1.50	292	0.96	20.76	5.23	0.089	22.38	0.196
8	11	374	0.040	23.0	1.55	289	1.06	20.65	5.16	0.097	29.40	0.249
9	11	385	0.045	22.0	1.58	282	1.16	20.44	5.07	0.104	29.06	0.244

Nato so bili dogodki pretvorjeni v trčne oziroma trenjske sile. Primer izmerjenega signala in prepoznanih maksimalnih vrednosti sil je prikazan za izbrano meritev na sliki 2. Časovni razmik med posameznimi vrhovi sil je bil imenovan časovni zamik med dogodki. Razmerje med merjenimi maksimalnimi silami in njihovimi pripadajočimi časovnimi zamiki je za izbrano meritev prikazano na sliki 3.

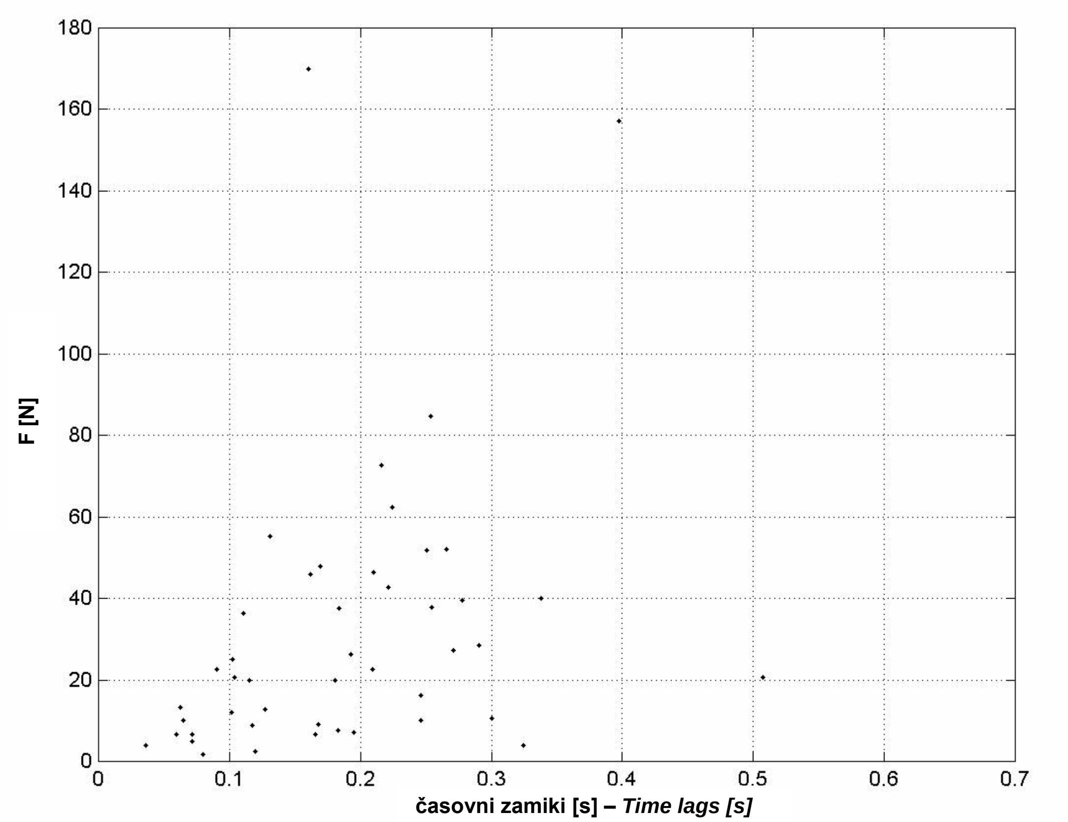
Zatem smo opravili statistično analizo izmerjenih maksimalnih sil in njihovih časovnih zamikov v odvisnosti od različnih merjenih parametrov toka iz preglednice 1. Maksimalne sile so najbolj linearno vzajemno soodvisne od brezdimenzijskih strižnih napetosti θ (Shieldsov parameter). Sliki 4 in 5 prikazujeta statistične parametre maksimalnih sil in časovnih zamikov za vse poskuse v odvisnosti od brezdimenzijske strižne napetosti θ.

Nadalje smo določili srednjo maksimalno silo za vsak poskus v odvisnosti od pripadajoče srednje hitrosti toka (slika 6) in brezdimenzijske strižne napetosti θ (slika 7).

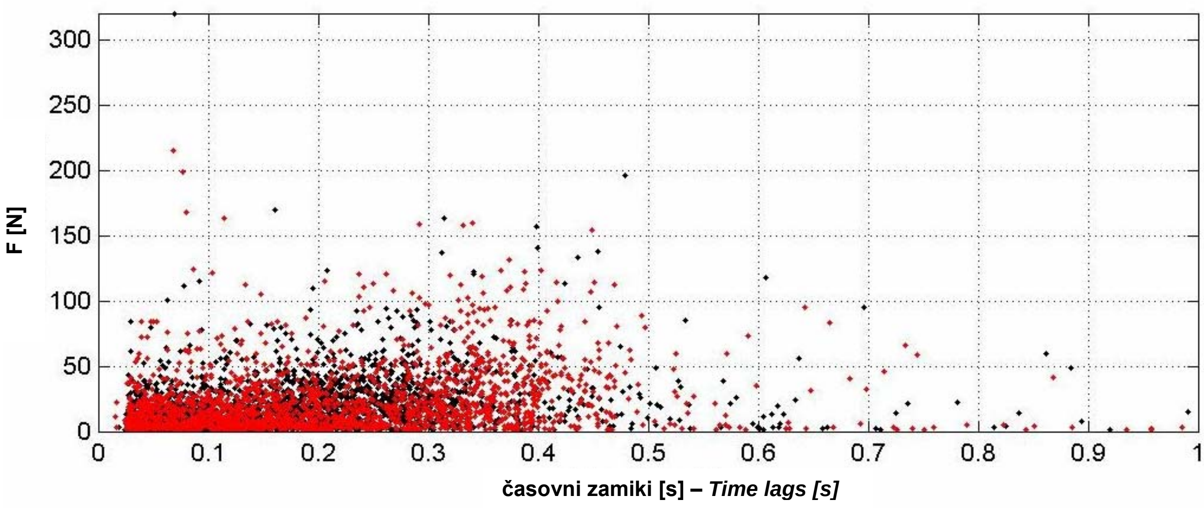
The recognised events were then converted into impact forces or friction forces. An example of a measured signal and recognised peak forces is given for one run in Figure 2. The time span between peaks was called the time lag between events. The relationship between measured peak forces and their time lags is shown for one run in Figure 3.

After that, a statistical analysis was performed of measured peak forces and their respective time lags as a function of diverse measured flow parameters, as presented in Table 1. For the maximal peak forces, the best linear correlation was found to be given by non-dimensional shear stresses θ (Shields parameter). The statistical parameters of peak forces and time lags for all tests as a function of the non-dimensional shear stress θ are shown in Figures 4 and 5.

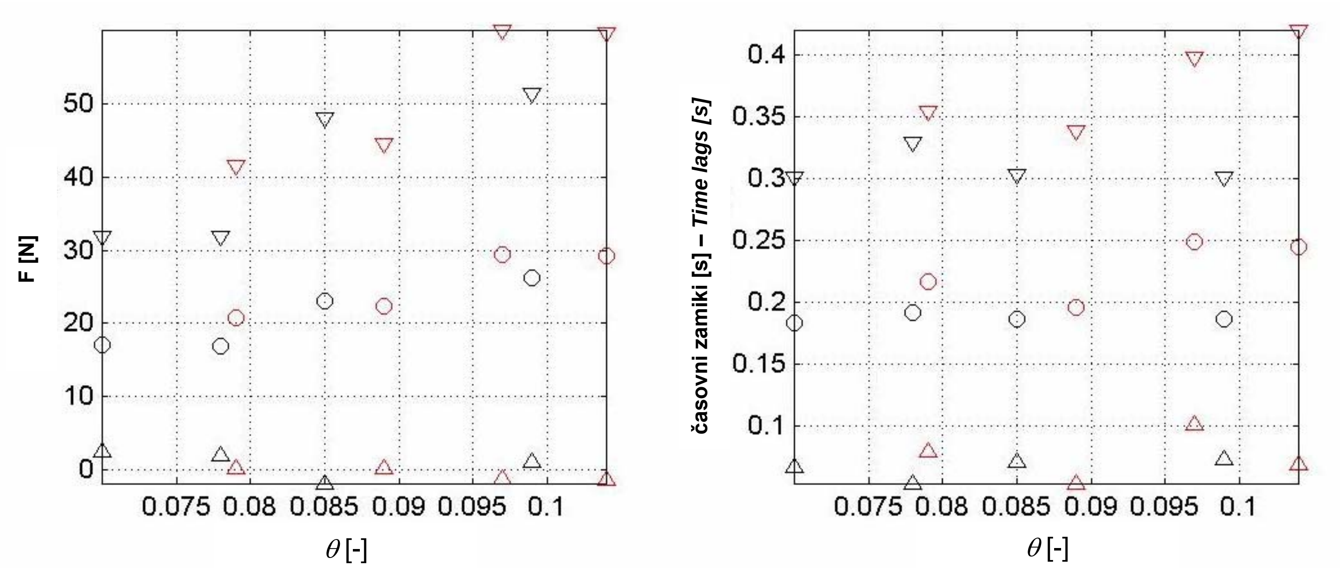
Furthermore, mean peak force for each test was determined and is shown in Figure 6 as a function of the corresponding water flow velocity, and in Figure 7 as a function of non-dimensional shear stress θ.



Slika 3. Razmerje med maksimalnimi silami *F* [N] in pripadajočimi časovnimi zamiki za dogodke meritve št. 9, poskus 4. Ta meritev je imela 47 prepoznanih dogodkov.
Figure 3. A relationship between peak forces F [N] and their time lags for events of run No. 9, test No. 4. There were 47 detected events for this run.

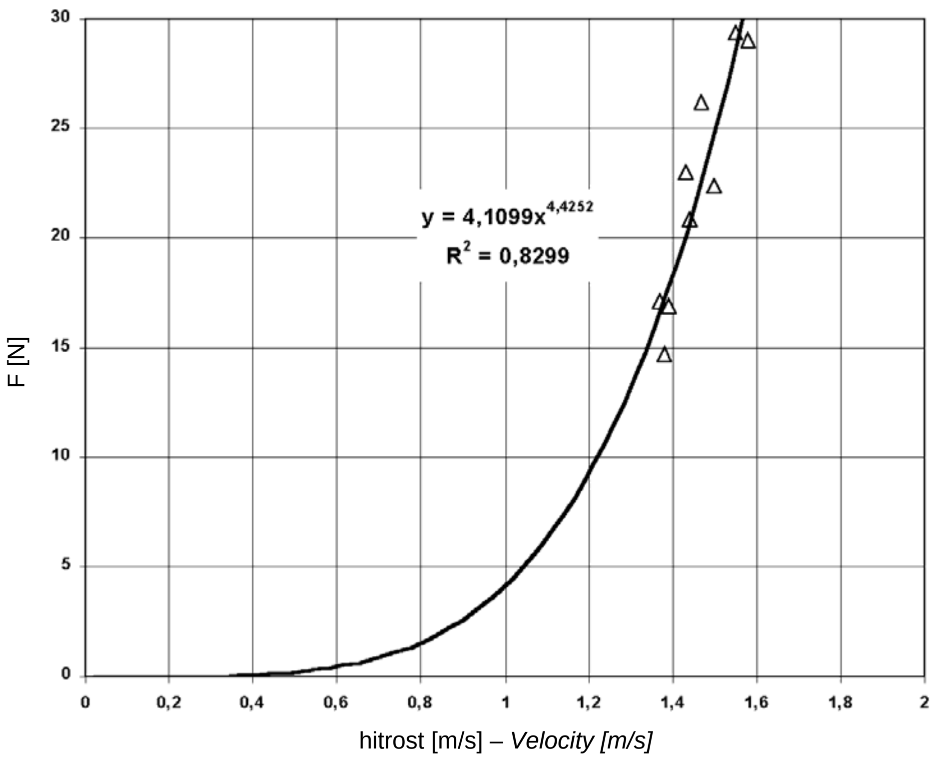


Slika 4. Vse maksimalne sile *F* [N] v odvisnosti od pripadajočih časovnih zamikov [s]. Ta niz meritev je obsegal skupaj 4213 prepoznanih dogodkov. Črne (temne) oznake prikazujejo srednje vrednosti maksimalnih sil za poskuse E1–E4 (skupaj 2150 prepoznanih dogodkov) in rdeče (svetle) oznake za poskuse E5–E9 (skupaj 2063 prepoznanih dogodkov).
Figure 4. All peak forces F [N] as a function of their respective time lags [s]. There were 4213 events altogether for this set of tests. Black (dark) symbols represent mean peak forces of tests E1–E4 (2150 detected events) and red (light) symbols those of tests E5–E9 (2063 detected events).



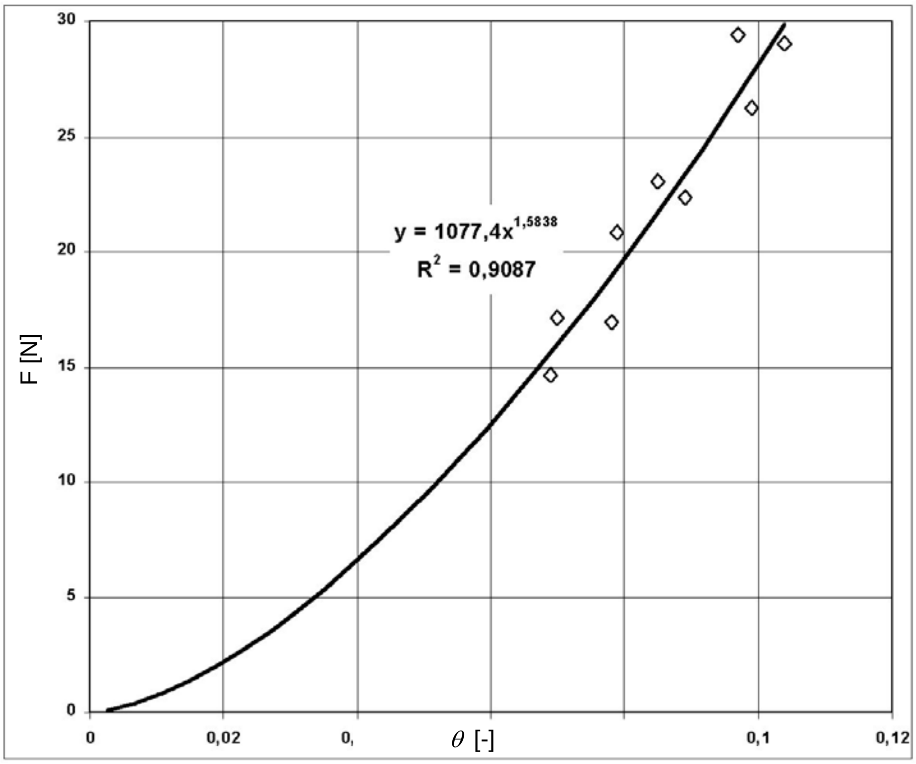
Slika 5. Statistična analiza maksimalnih sil F [N] in časovnih zamikov [s] med njimi v odvisnosti od brezdimenzijske strižne napetosti θ [-]. Krožci 'o' predstavljajo srednje vrednosti ter trikotniki "∇" in "Δ" predstavljajo srednje vrednosti ± 1 standardno odstopanje. Črne (temne) oznake prikazujejo srednje vrednosti maksimalnih sil za poskuse E1–E4 in rdeče (svetle) oznake za poskuse E5–E9.

Figure 5. Statistical analyses of peak forces F [N] and time lags [s] between them, as a function of non-dimensional shear stress θ [-]. Circles 'o' represent mean values and triangles "∇" and "Δ" represent mean values ± one standard deviation. Black (dark) symbols represent mean peak forces of tests E1–E4 and red (light) symbols those of tests E5–E9.

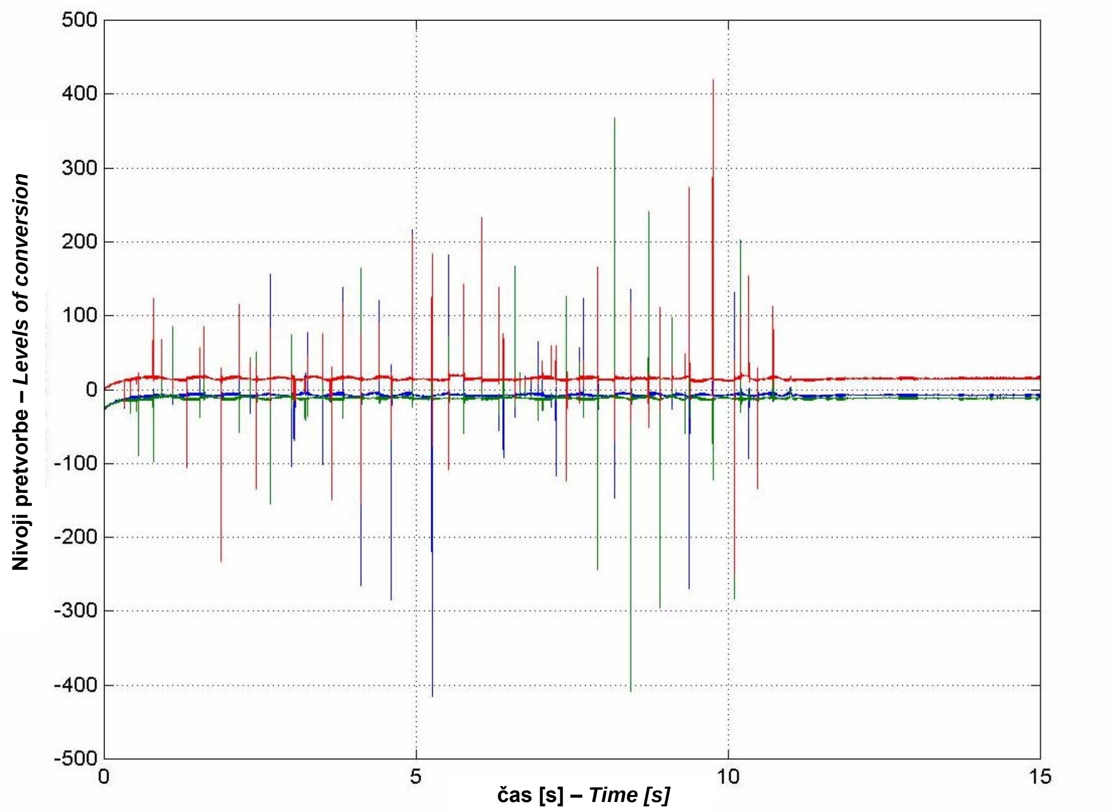


Slika 6. Srednja maksimalna sila F [N] za vsak poskus prvega niza poskusov v nagibnem žlebu v odvisnosti od pretočne hitrosti vode [m/s].

Figure 6. Mean peak force F [N] for each experiment of the first set of tests in the tilting flume as a function of water flow velocity [m/s].



Slika 7. Srednja maksimalna sila F [N] za vsak poskus prvega niza poskusov v nagibnem žlebu v odvisnosti od brezdimenzijske strižne napetosti θ [-].
Figure 7. Mean peak force F [N] for each experiment of the first set of tests in the tilting flume as a function of non-dimensional shear stress θ [-].



Slika 8. Značilni signal treh merjenih pospeškov v nagibnem žlebu pri 1 % padcu dna.
Figure 8. Typical signal of three measured accelerations in the tilting flume at 1 % slope.

Vsi prikazani rezultati na slikah 3 do 7 so bili izmerjeni z uporabo prodnika vohuna z enim enoosnim pospeškometrom. Dobljeni rezultati so bili ocenjeni kot realističen prikaz dogajanja v laboratorijskem žlebu in torej dovolj dobri, da nadaljujemo z razvojem sledila. Tako smo vanj vgradili še dva enakovredna enoosna pospeškometra. Vsi nadaljnji rezultati so bili dobljeni s tako opremljenim prodnikom.

Slika 8 prikazuje značilen signal izmerjenih pospeškov za izbrano meritev pri 1 % nagiba dna žleba, hitrosti toka 1,09 m/s in globini toka 16 cm.

Nato smo razvili programsko orodje za avtomatsko prepoznavanje maksimalnih vrednosti ločenih dogodkov, to je trkov v izmerjenem signalu pospeškov. Pri tej avtomatski analizi smo uporabili vektorsko vsoto pospeškov, da bi v signalu določili okno, v katerem se je pojavil dogodek. Za analizo dolžine in usmeritve vektorja trčne ali trenjske sile smo nato uporabili posamezne komponente, torej izvirni signal in ne njihovo vektorsko vsoto.

All the results shown on Figures 3 to 7 were obtained by the SPY-Cobble with only one built-in one-axis accelerometer sensor. The obtained results were evaluated as a realistic expression of circumstances in the laboratory flume and as such to be good enough to proceed with the cobble development. Therefore, two identical sensors were added to it. All following results were obtained using the SPY-Cobble with three sensors.

The typical signal of measured accelerations for one run with 1 % of the flume bottom slope, the water velocity of 1.09 m/s and the water depth of 16 cm is shown on Figure 8.

We then developed a software system that automatically recognises the maximum values of separated events, namely hits in the signals of acceleration. When we automatically detect the windows of the vector sum in which the hits are present, we go back to its components, which are our true acceleration signal and which determine the force vector length and direction.

2.2 DRUGI NIZ LABORATORIJSKIH POSKUSOV

Drugi sistematični niz laboratorijskih poskusov smo opravili v istem 10 m dolgem in 0,81 m širokem nagibnem laboratorijskem žlebu na Svobodni univerzi v Berlinu.

Njegovo dno je bilo za prvi del tega niza meritev (del A) pokrito z gibljivimi naravnimi prodniki s srednjim premerom d_m = 86 mm in d_{90} = 93 mm (prodniki so bili veliki od 20 do 120 mm). Te razmere so ponovile razmere iz prvega niza laboratorijskih meritev. V delu A smo izvedli 6 poskusov (A1 do A6), vsak poskus je bil sestavljen iz treh posameznih meritev. V času posamezne meritve je bilo gibljivo dno laboratorijskega žleba praktično stabilno in vodni tok je erodiral le nekaj prodnikov (do nekaj 10 kilogramov). Izmerjena prodonosnost je bila manjša od 3 kg/s. Ta vrednost se zdi visoka, vendar se je prodnik vohun le izjemoma zaletel v drugi prodnik v gibanju in njegovo gibanje v žlebu je bilo praktično neodvisno od prodonosnosti.

Za drugi del tega niza meritev (del B) smo iz žleba odstranili naravne prodnike in izvedli 7 poskusov (B1 do B7, vsakič 1 meritev) na

2.2 SECOND SET OF LABORATORY TESTS

In the same tilting laboratory flume at the Free University in Berlin (10-m long and 0.81-m wide), we systematically conducted the second set of laboratory tests.

Its bottom was for the first part of the test (part A) covered with freely moving natural clasts with the arithmetic mean d_m = 86 mm and d_{90} = 93 mm, respectively (clasts were in the range between 20 mm and 120 mm). This situation reassembles the situation in the first set of test. In part A, we performed 6 tests (A1 through A6) comprised of 3 runs each. During each run the movable bed of the flume was practically stable and only some clasts (up to few tens of kilograms) were eroded. The measured sediment transport rates were lower than 3 kg/s. This value might seem to be high, but the SPY-Cobble was rarely hit by a moving clast and its movement was practically undisturbed by sediment transport.

For the second part of the test (Part B), we have taken out the natural clasts and performed 7 tests (B1 through B7, 1 run each) jeklenem dnu brez prodnikov.

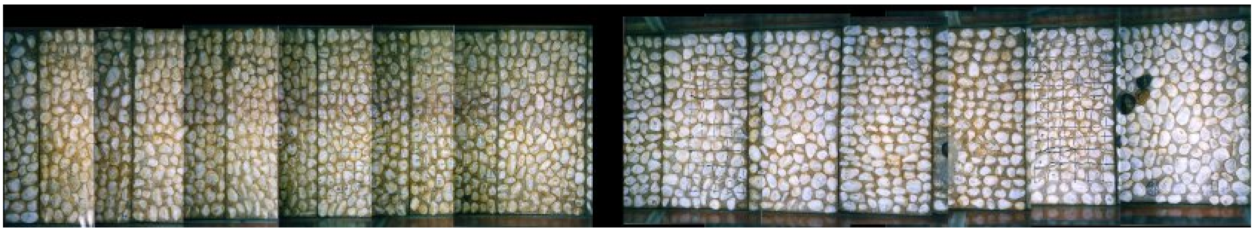
Za tretji del tega niza poskusov (del C) smo dno laboratorijskega žleba prekrili z betonskimi ploščami, v katerih so bili vliti naravni prodniki (slika 9) – negibljivo dno. Izvedli smo 10 poskusov (C1 do C10, vsakič 5 meritev). Med vsako meritvijo smo merili različne parametre toka in iz njih izračunali druge relevantne parametre, prikazane v preglednici 2.

on the steel bottom, with no clasts present in the flume at all.

For the third part of the test (Part C), the bottom was covered by concrete plates with cast natural clasts (Figure 9) – fixed bed – and 10 tests were performed (C1 through C10, 5 runs each). During each run, various flow parameters were measured and calculated, as presented in Table 2.

Preglednica 2. Pregled drugega niza laboratorijskih meritev v nagibnem žlebu (za razlago parametrov glej preglednico 1).
Table 2. On overview of the second set of laboratory tests in the tilting flume (for definition of parameters see Table 1).

			meritev – *Measured*			račun – *Calculated*					analiza – *Analysed*	
poskus *Test*	meritve *Runs* [–]	dogodki *Events* [–]	*S* [-]	*h* [cm]	*v* [m/s]	*Q* [l/s]	*Fr* [-]	k_{St} [$m^{1/3}$/s]	*c* [-]	*θ* [-]	*F* [N]	*t* [s]
A1	3	183	0.035	24.5	1.45	288	0.88	19.80	5.00	0.090	52.92	0.16
A2	3	154	0.040	23.5	1.48	282	0.95	19.43	4.87	0.099	35.28	0.16
A3	3	144	0.045	23.0	1.50	280	1.00	18.84	4.71	0.109	37.00	0.18
A4	2	86	0.050	22.5	1.51	275	1.03	18.25	4.55	0.119	43.22	0.18
A5	3	140	0.055	22.0	1.55	276	1.11	18.14	4.50	0.128	40.89	0.17
A6	3	121	0.0625	21.0	1.64	279	1.31	18.05	4.57	0.138	42.57	0.18
B1	1	121	0.020	13.5	2.32	254	4.06	62.34	14.26	0.028	8.84	0.11
B2	1	62	0.025	13.0	2.37	250	4.40	58.41	13.27	0.034	10.43	0.06
B3	1	59	0.030	13.0	2.41	254	4.55	54.22	12.32	0.041	9.02	0.06
B4	1	56	0.035	12.5	2.44	247	4.86	52.17	11.78	0.046	8.63	0.07
B5	1	55	0.040	12.0	2.50	243	5.31	51.38	11.52	0.051	9.55	0.07
B6	1	48	0.045	12.0	2.55	248	5.52	49.41	11.08	0.057	9.96	0.08
B7	1	52	0.050	12.0	2.58	251	5.65	47.43	10.63	0.063	9.81	0.07
C1	5	701	0.005	18.5	0.83	124	0.38	36.15	8.71	0.010	12.86	0.09
C2	5	318	0.010	16.0	1.09	141	0.76	36.98	8.70	0.017	32.27	0.17
C3	5	181	0.015	14.0	1.37	155	1.37	41.49	9.55	0.022	49.10	0.20
C4	5	146	0.020	13.0	1.51	159	1.86	41.61	9.45	0.027	59.05	0.21
C5	5	142	0.025	13.0	1.60	169	2.01	39.43	8.96	0.034	55.01	0.19
C6	5	147	0.030	12.0	1.66	161	2.34	39.39	8.83	0.038	62.52	0.19
C7	5	117	0.035	11.0	1.71	152	2.71	39.81	8.80	0.041	69.55	0.20
C8	5	143	0.040	11.0	1.77	158	2.90	38.55	8.52	0.046	56.94	0.17
C9	5	120	0.045	10.0	1.81	147	3.34	39.60	8.61	0.047	62.47	0.16
C10	5	117	0.050	10.0	1.86	151	3.53	38.61	8.40	0.053	72.54	0.18



Slika 9. Pogled na dno laboratorijskega žleba za del C drugega niza laboratorijskih meritev. Dno je bilo prekrito z betonskimi ploščami z vlitimi naravnimi prodniki (število prodnikov na m^2 je bilo v povprečju 35, minimalni premer d_{min} = 4 cm, srednji premer d_m = 7 cm in maksimalni premer d_{max} = 10 cm). Smer toka v 0,81 m širokem žlebu je bila z leve na desno.
Figure 9. A view of the flume bottom for part C of the second set of laboratory tests. The bottom was covered by concrete plates with fixed (cast) natural clasts (number of clasts per m^2 was 35 on average, minimum diameter d_{min} = 4 cm, mean diameter d_m = 7 cm, and maximum diameter d_{max} = 10 cm). The flow direction in the 0.81 m wide flume is from left to right.

Merjeni pospeški vsake meritve se lahko prikažejo v obliki zvočnega zapisa. Vsak dogodek lahko slišimo in tako dobimo precej jasen vtis o dogajanju. Vse zvočne zapise smo ustvarili iz originalnih meritev pospeškov s pomočjo funkcij "sound.m" in "soundsc.m" v programskem okolju Matlab®.

Sliki 10 in 11 prikazujeta rezultate analize merjenih pospeškov, in sicer ločeno za posamezne dele A, B in C tega niza laboratorijskih poskusov. Slika 10 prikazuje odvisnost maksimalnih sil in njihovih časovnih zamikov. Slika 11 prikazuje statistično analizo maksimalnih sil v odvisnosti od brezdimenzijske strižne napetosti θ. Nadalje je bila določena srednja maksimalna sila za vsak poskus, in sicer v odvisnosti od hitrosti toka (slika 12) oziroma v odvisnosti od brezdimenzijske strižne napetosti θ (slika 13).

Measured accelerations during each run can also be presented in a form of a sound file. In this case each event can be heard and quite a realistic impression can be achieved only by listening to a sound file. All sound files have been converted from original acceleration measurements using MATLAB® functions "sound.m" and "soundsc.m".

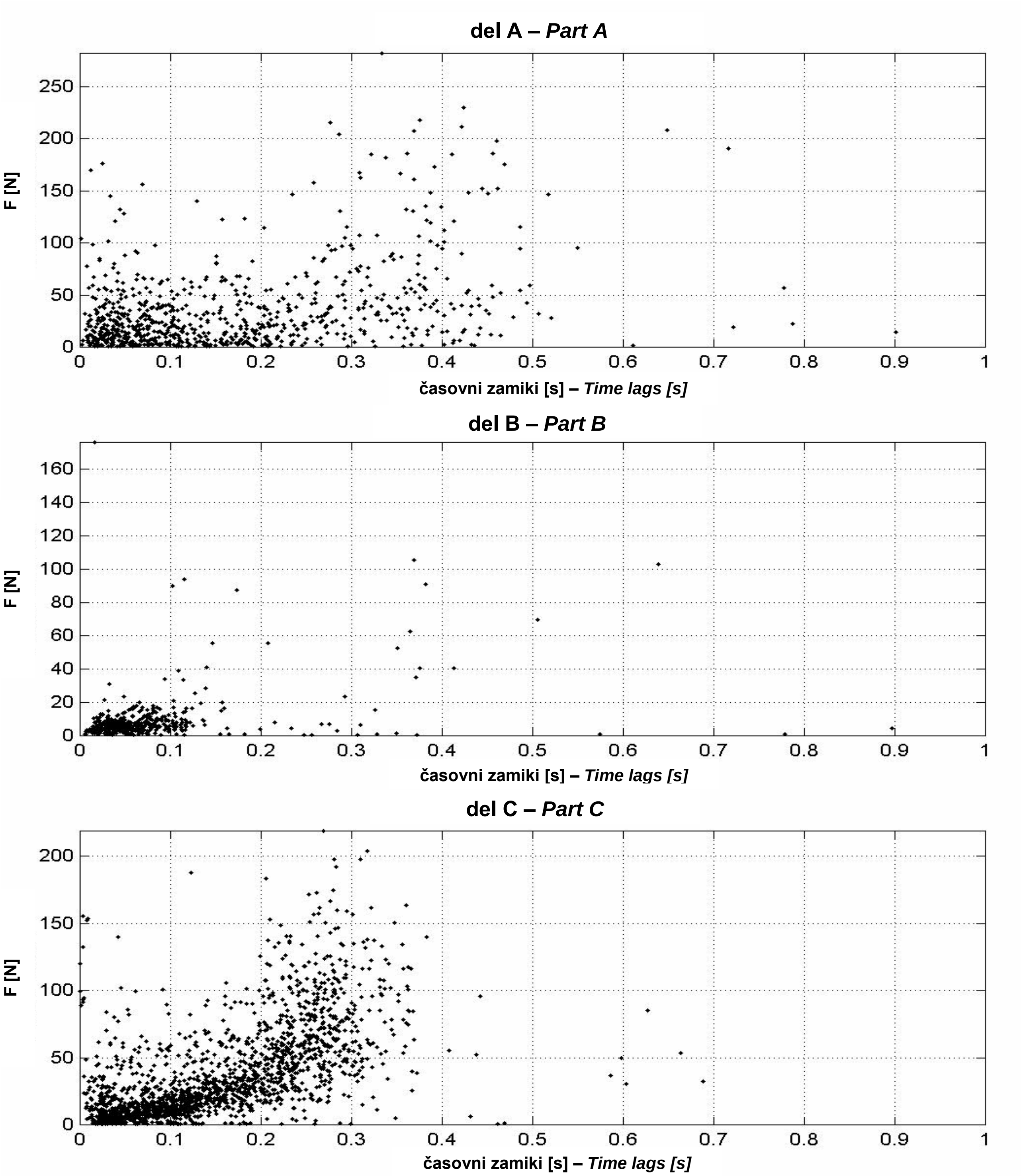
The results of the analyses of measured accelerations are presented in Figures 10 and 11, separately for each part of the tests (A, B, and C). Figure 10 presents the dependence of peak forces and their respective time lags. Figure 11 presents statistical analyses of peak forces as a function of the non-dimensional shear stress θ. Furthermore, mean peak force for each test was determined and it is shown in Figure 12 as a function of the corresponding water flow velocity, and in Figure 13 as a function of non-dimensional shear stress θ.

3. RAZPRAVA

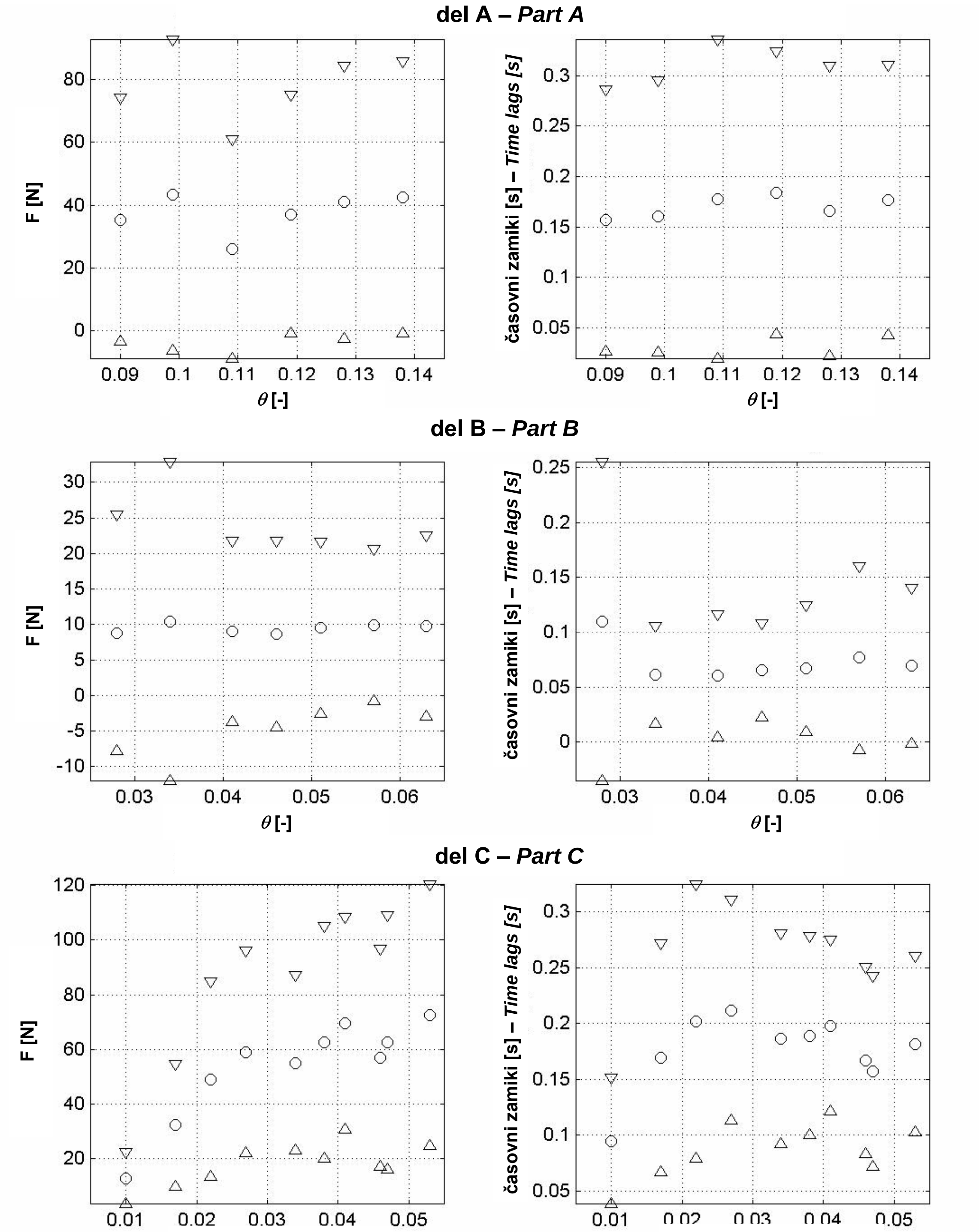
Opravljena raziskava je potrdila, da je prodnik vohun dovolj robusten in popolnoma uporaben za meritve dinamike posameznih sedimentnih delcev v turbulentnem toku. Kljub temu ga je treba obravnavati kot uporaben prototip. Glavna omejitev pri njegovi uporabi je laboratorijsko okolje, v katerem ga lahko uspešno uporabimo, saj bi za uporabo v naravnem okolju najprej morali dodati npr. pasivni radijski oddajnik, da bi lahko napravo po meritvah znova našli.

3. DISCUSSION

The SPY-Cobble has proved to be robust enough and fully functional by means of measurements of single coarse particle dynamics in turbulent flows. Still, it should be considered as a functional prototype. The major limitation in its use is the laboratory environment, where it can be used sucessfully and usefully, because modifications would be needed for its recovering in a natural environment, such as adding a passive radio transmitter.

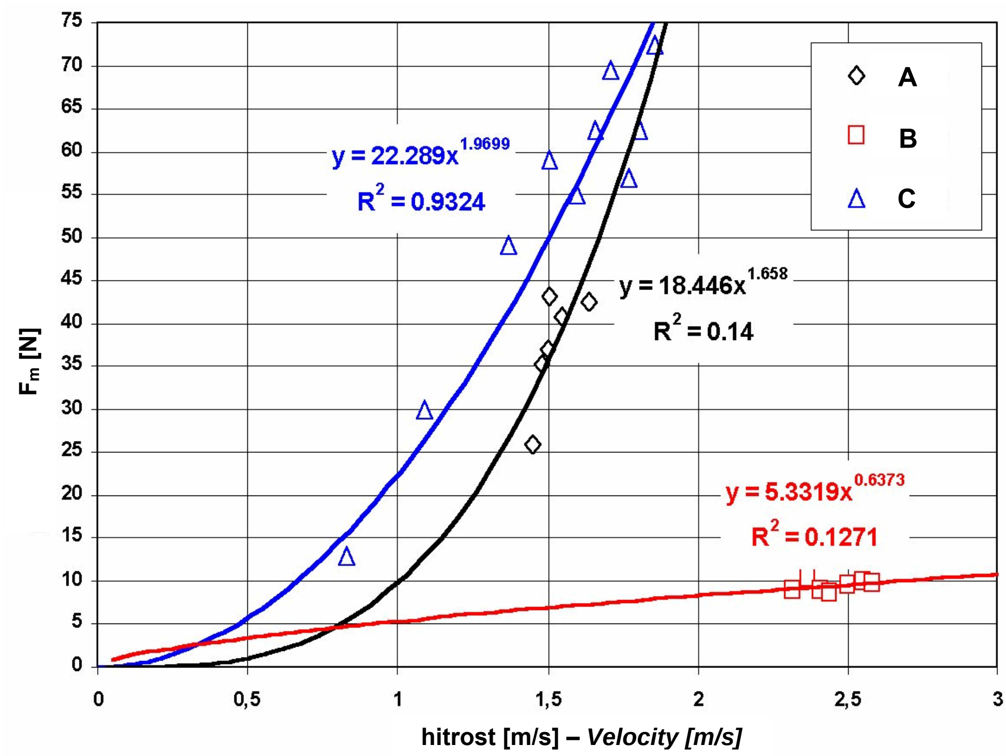


Slika 10. Prikaz maksimalnih sil *F* [N] v odvisnosti od časovnih zamikov [s], posebej za vse tri dele drugega niza laboratorijskih poskusov v nagibnem laboratorijskem žlebu (del A – gibljivi naravni prodniki, del B – jekleno dno, del C – vliti naravni prodniki). Za del A je bilo prepoznanih 828 trkov, za del B je bilo trkov 453 in za del C 2132 trkov.
Figure 10. All peak forces F [N] as a function of their respective time lags [s], given separately for all three parts of the second set of tests in a tilting flume (A – movable natural clasts, B – steel bottom, and C – fixed natural clasts). For part A, there were 828, for part B 453, and for part C 2132 detected peaks.

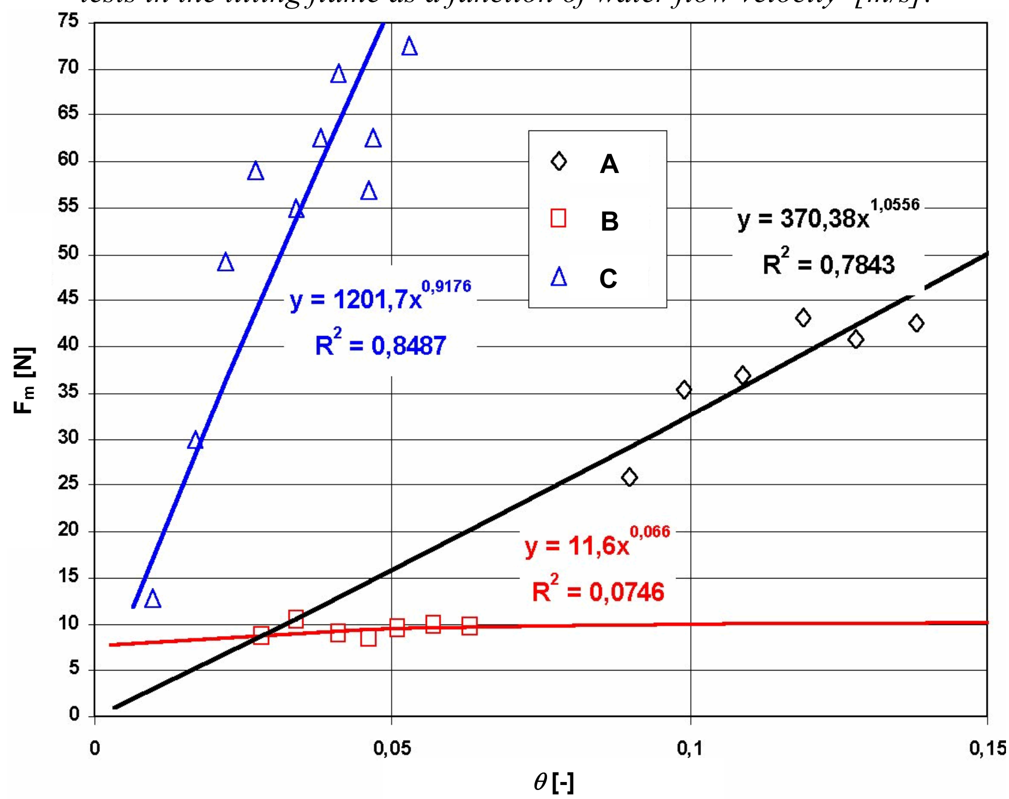


Slika 11. Statistična analiza maksimalnih sil F [N] in časovnih zamikov [s] med trki v odvisnosti od brezdimenzijske strižne napetosti θ za vse tri dele drugega niza poskusov v nagibnem laboratorijskem žlebu (del A – gibljivi naravni prodniki, del B – jekleno dno, del C – vliti naravni prodniki). Krožci 'o' označujejo srednje vrednosti parametrov, trikotniki "∇" in "Δ" pa srednjo vrednost ± ena standardna deviacija.

Figure 11. Statistical analyses of peak forces F [N] and time lags [s] between them, as a function of non-dimensional shear stress θ given separately for all three parts of the second set of tests in a tilting flume (A – movable natural clasts, B – steel bottom, and C – fixed natural clasts). Circles 'o' represent mean values and triangles "∇" and "Δ" represent mean values ± one standard deviation.



Slika 12. Srednja maksimalna sila F_m [N] za vsak poskus treh delov (A, B in C) drugega niza laboratorijskih poskusov v nagibnem žlebu v odvisnosti od pretočne hitrosti vode [m/s].
Figure 12. Mean peak force F_m [N] for each run of three parts (A, B, and C) of the second set of tests in the tilting flume as a function of water flow velocity [m/s].



Slika 13. Srednja maksimalna sila F_m [N] za vsak poskus vseh treh delov (A, B in C) drugega niza laboratorijskih poskusov v nagibnem žlebu v odvisnosti od brezdimenzijske strižne napetosti θ [-].
Figure 13. Mean peak force F_m [N] for each run of three parts (A, B, and C) of the second set of tests in the tilting flume as a function of non-dimensional shear stress θ [-].

Druge lastnosti prototipa, kot so hitrost vzorčevanja, razpoložljivi prostor pomnilnika ali hitrost prenosa podatkov, lahko dosežemo s spremembo določenih elektronskih delov. Vendar obstaja možnost, da tovrstne spremembe negativno vplivajo na minimalno porabo energije, kot jo ima merilna naprava sedaj.

Dva niza opravljenih laboratorijskih poskusov v nagibnem laboratorijskem žlebu ob različnih hidravličnih pogojih sta pokazala, da lahko prodnik vohun uspešno meri kontaktne sile in natančno poda čase teh kontaktov med gibanjem posameznega sedimentnega delca (sliki 10 in 11). Opravljene meritve s prodnikom vohunom lahko opišemo kot meritve gibanja posameznega sedimentnega delca v čisti vodi in ob nepomičnem dnu. Če je bila v posameznem primeru prisotna šibka prodonosnost, jo lahko zanemarimo, saj praktično ni imela omembe vrednega vpliva na dinamiko gibanja prodnika vohuna. To seveda ne bi več držalo v primeru popolnoma gibljivega dna in visoke prodosnosti. Take soodvisnosti ob omenjenih hidravličnih razmerah je treba s prodnikom vohunom še raziskati.

Opravljene laboratorijske meritve so podprle veljavnost kvadratnega zakona trka, ki določa, da je maksimalna trčna sila odvisna od druge potence trčne hitrosti. Res je, da nismo neposredno merili hitrosti prodnika vohuna, toda slika 12 potrjuje veljavnost omenjenega zakona. Za del A ta zakon ne velja popolnoma, saj so bili prodniki v laboratorijskem žlebu gibljivi. Tako se ob kontaktih med njimi in prodnikom vohunom niso pojavili le centrični trki. To je še toliko bolj veljavno za meritve v delu B, kjer je bilo dno žleba sestavljeno iz jeklenih plošč. Pri takih razmerah so bile izmerjene visoke hitrosti toka zaradi majhne hrapavosti ostenja (slika 12). Prodnik vohun je v glavnem drsel ali se kotalil po dnu žleba in le deloma udarjal ob dno. To je poglavitni vzrok, da je odvisnost srednje maksimalne sile od hitrosti toka v tem primeru konstantna in ne kvadratna. Tudi maksimalne sile so nekoliko nizke, saj je prodnik vohun v glavnem drsel in se kotalil in ni udarjal ob jekleno dno. Hidravlične razmere v delu C nato znova popolnoma potrjujejo veljavnost kvadratnega zakona trkov (slika 12). Dno žleba je bilo

Other features such as sampling speed, space available for storage and speed of download could be improved by changes of certain electronic parts, although these changes might negatively affect the minimal power consumption, which the device has at the present.

Two sets of measurements in the tilting flume under different hydraulic conditions have proved that the SPY-Cobble can successfully measure contact forces and give precise times of contacts during single particle transport (Figures 10 and 11). The measurements conducted using SPY-Cobble can be defined as single particle transport in clear water and stable bed. When there was weak sediment transport in some runs, we could neglect it because it had practically no significant influence on the dynamics of the SPY-Cobble. This would not be true in case of fully movable bed and high sediment transport rates. This interrelations under such hydraulic conditions are still to be investigated using the SPY-Cobble.

The conducted laboratory measurements have supported the validity of quadratic impact law. It is true that we did directly measure the tracer velocity, but Figure 12 supports the validity of the quadratic impact law. For part A, this law is not fully correct, because clasts in the flume were movable and during the impacts or contact events between them and the tracer, centric impacts were not the only type of collisions. This is even more true for the runs in part B, where the flume bottom was made of steel plates. Under such conditions very high water flow velocities were measured due to low roughness of the flume (Figure 12). The SPY-Cobble was mainly sliding, partially rolling, and practically had little impact with the flume bottom. That is why in this case the functional dependence of the mean detected peak forces on the water flow velocity is constant rather than quadratic. Also peak forces are rather low, because the tracer was mainly sliding and rolling and not impacting the steel plates. But hydraulic conditions in part C gave a full validity of the quadratic impact law (Figure 12). The flume bottom was covered by fixed natural clasts, cast in concrete plates (Figure 9).

prekrito z betonskimi ploščami, v katerih so bili vliti (negibljivi) naravni prodniki (slika 9).

Mnogo manj je možno ugotoviti o časovnih zamikih med posameznimi trki oziroma trčnimi dogodki (slika 11). Kljub temu je očitno, da so časovni zamiki v primeru kotaljenja ali drsenja (del B) v povprečju mnogo manjši kakor v primeru prevladujočega poskakovanja (del A in C).

Ta očitna razlika med delom B in deloma A in C se lahko sliši, če pozorno prisluhnemo izmerjenim zvočnim zapisom meritev pospeškov.

Analiza merjenih maksimalnih sil (slika 13) in časovnih zamikov (slika 11) bo v prihodnje usmerjena v oblikovanje ustrezne slučajne porazdelitve teh dveh parametrov. Tak pristop bo pomagal izdelati generator sintetičnih časovnih zaporedij kontaktov in pripadajočih maksimalnih sil, ki bi kar najbolj ustrezale naravnim dogodkom pri premeščanju sedimentov. Glavni namen bo poiskati soodvisnost med hidravličnimi parametri (hitrost toka, globina toka, strižna napetost), sedimentološkimi parametri (velikost delca, gostota delca) in parametri slučajne porazdelitvene funkcije.

4. ZAKLJUČKI

Na osnovi opravljene raziskave lahko zaključimo, da obstaja očitna potreba po nadaljnjem razvoju obstoječih vrst sledil kakor tudi po razvoju novih vrst sledil z uporabo novih tehnologij. Če so magnetna in radijska sledila dovolj dobra za sledenje njihovemu gibanju v času poplavnega vala z namenom določiti obdobja gibanja in mirovanja ter njihovo razporeditev, potem je nujen nov tip sledila, če želimo pridobiti nov vpogled v dinamiko premeščanja plavin.

Novorazviti instrumentizirani prodnik vohun je primer bolj kompleksnega sledila, ki je bil zaradi svoje proizvodne cene (nekaj tisoč €) testiran le v laboratorijskih razmerah. Ker podobnih sledil v svetu še ni, tudi ni na voljo meritev, ki bi jih lahko vzeli za primerjavo. Ocena uporabnosti je bila zato izvedena s pomočjo teorije trkov in kvadratnega zakona trka.

Raziskava je pokazala, da je prodnik vohun uporabno raziskovalno orodje, ki daje

Much less can be stated about the time lags between individual impacts or contact events (Figure 11). Nevertheless, it is obvious that under rolling and sliding, as in part B, these lag times are much lower on average than in the case of saltating movements, as prevailing in parts A and C.

These clear differences between part B on one hand and parts A and C on the other, can also be heard, namely by carefully listening to the sound files from these measurements.

A further analysis of the measured peak forces (Figure 13) and time lags (Figure 11) will go into creating an appropriate stochastic distribution of these two parameters. This will help to establish a generator of synthetic time series of contacts and corresponding peak forces, which should be able to match natural sediment transport events as closely as possible. The main task will be to find the correlation between hydraulic parameters (water flow velocity, water depth, shear stresses), sedimentological parameters (particle size and density), and parameters of stochastic probability distribution function.

4. CONCLUSIONS

Based on the research, we can conclude that there is an obvious need to further develop the existing types of sediment tracers, as well as to develop new types of tracers, using more advanced technologies. If magnetic and radio tracers are good enough to follow a tracer during a flood to determine moving and resting periods and their distribution, then a new type of a tracer is needed if more insight into the dynamics of sediment transport is expected.

A new instrumented tracer SPY-Cobble is an example of a more sophisticated tracer, which, because of its costs (several thousand €), has only been tested in the laboratory environment. Because there are no similar tracers developed in the world, there are also no measurements that could be taken for comparison pourposes. Assessment of its usefulness was therefore done on the basis of impact theory and the quadratic impact law.

The tracer has proven to be a valuable

naslednje neprekinjene vrednosti parametrov premeščanja grobih sedimentih delcev:

- točne čase kontaktov z okoliškimi trdimi telesi (pesek, prod, groblja, skale, samice);
- vršne intenzitete dinamičnih trenjskih ali trčnih sil, ki delujejo na sledilo v času teh kontaktov;
- srednjo hitrost sledila in
- način gibanja med posameznimi kontakti (kotaljenje, drsenje, poskakovanje).

Za določitev dejanske poti sledila bi morali v prodnik vgraditi dodatni enoosni sensor.

Opisani podatki omogočajo raziskovalcu oblikovati bolj dodelan model premeščanja grobih sedimentnih delcev, npr. na osnovi Lagrangeovega pristopa in z uporabo statističnih in slučajno porazdeljenih parametrov. Možen je razvoj modela premeščanja z uporabo mehanike kontakta in lastnosti materialov, ki bi se kombinirali z merjenimi vrednostmi pomembnih parametrov, kot so koeficient odboja "e" ali trajanje trka "t".

Za bolj kompleksne modele premeščanja, kot je to bilo nakazano zgoraj, je treba prodnik vohun razviti v novo fazo. Če bi ga želeli uporabiti kot uporabno raziskovalno orodje v dolinskih prodonosnih rekah in ne le v strmih hudournikih, je treba predvsem zmanjšati njegovo velikost.

research tool, which gives the following continuously defined parameters of transport of coarse sediment particles:

- precise times of contacts with surrounding bodies (sand, gravel, pebbles, cobbles, boulders);
- peak intensities of dynamic friction or impact forces acting upon the tracer during these contacts;
- mean tracer velocity, and
- way of movement between contacts (rolling, sliding, or saltating).

For the determination of the pathway of the tracer, an additional one-axis accelerometer should be built into it.

These data enable a researcher to design a more profound model of coarse sediment transport, e.g. based on the Lagrangian approach and statistically or stochastically distributed parameters. One could even develop a transport model using contact mechanics and material properties, combining them with the measured values of important parameters such as restitution coefficient "e" or duration of impacts "t".

For more sophisticated transport models, one should further develop the SPY-Cobble. Especially, one should reduce its size, in order to use it as a relevant research tool not only in steep torrents, but also in gravel-bed rivers.

ZAHVALA

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