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Physical Modelling of Water Flow in 'Wild River' Type Water Slide

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Abstract

The results of physical modelling of water flow in 'Wild River' type slide are presented. The hydraulic investigation concerns the water slide being a component of 'Świat Wodny Nemo' water-pool complex in Sopot. The laboratory tests were carried out on a model of the slide installed in the Laboratory of Hydro and Environmental Engineering of the Gdańsk University of Technology. Generally, the water flow observed in the open channel and reservoir system can be classified as steady and rapidly varied. The large number of local, hydraulic effects was observed along the whole slide track due to strongly varying bottom slopes and curvatures of channel bends.

1. Introduction

The main purpose of the paper is the analysis of water flow in the 'Wild River' type object, which is a component of the 'Świat Wodny Nemo' water-pool complex. The object is a water slide composed of five basins connected by a track formed of open channels (Fig. 1a,b) built for recreation use. In the channels, free surface water flow due to gravity occurs. Excluding the inlet and outlet reservoirs, the main track is composed of four open channel segments of widths varying from 1 to 2 metres. The slide track connects 3 intermediate (repose) basins. The length of the main track along its axis is 72 m and difference of bottom level at start and finish section of water slide is 4.5 m. According to project assumptions the object should work within a semi-closed cycle with constant operation discharge of range 0.60 or 0.85 m^3/s. Because of "Wild River" project copyright other object details can not be described in this paper.

Concerning variation of the hydraulic parameters (flow velocity, depth) in time, flows in open channels are classified as steady or unsteady. Moreover, if flow parameters do not change in space, the flow is defined as uniform, otherwise it is classified as non-uniform. Additionally, considering the curvature of streamlines, presence of vertical accelerations, rate of change of depth in time and space and possibility of transits from subcritical to supercritical and vice versa, the flow in open channels can be defined as gradually or rapidly varied (Chow 1959).

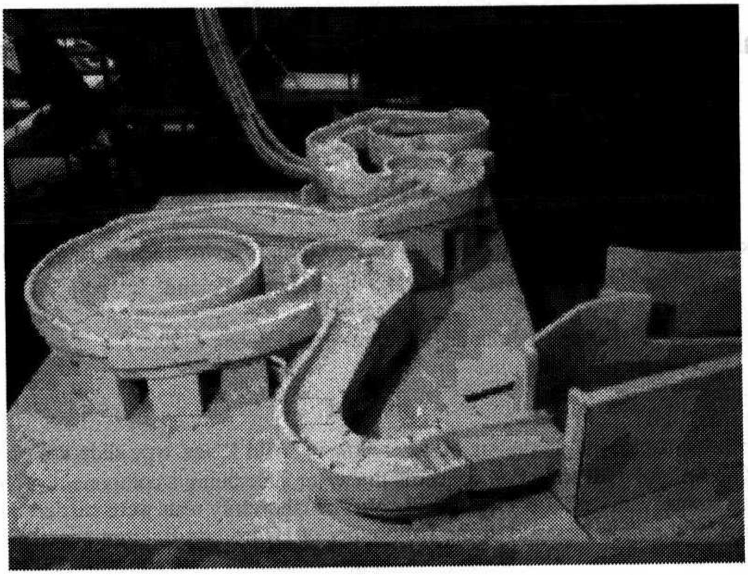

Fig. 1a. Model of water slide – view

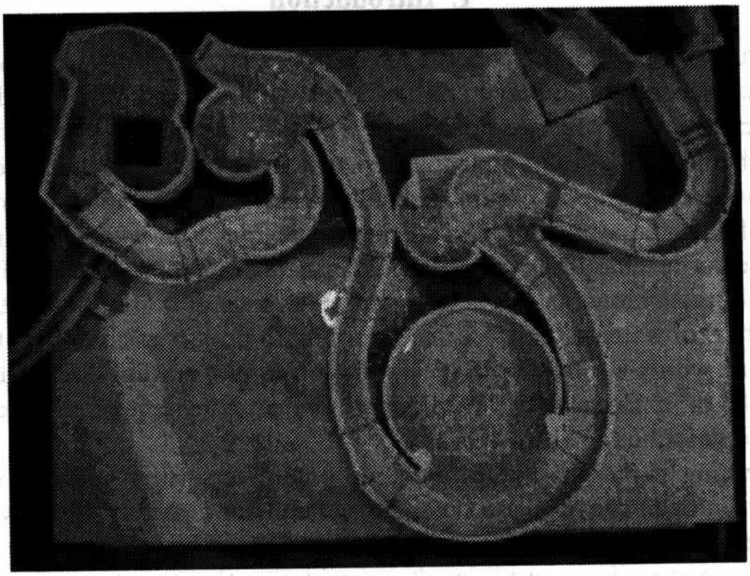

Fig. 1b. Model of water slide – plan

The occurrence of these different types of flow in the same region and at the same time is rather rare in natural channels and hydraulic structures. Thus usually for practical cases either steady or unsteady flow is considered. In the case of the water slide, only during the object start-up unsteady flow is observed. Then the flow becomes steady due to constant operation conditions. Considering the variable shape of channels and reservoirs along the slide route, water flow must be classified as non–uniform (variable in space). However, the most characteristic feature of the flow in the considered object, distinguishing this case from the typical flow in an open channel, is a large number of the local effects occurring along the whole length of the slide.

In most practical cases, either gradually varied flows, present in the open channels, rivers and shallow water reservoirs or rapidly varied flow observed locally, for instance near the hydraulic structures, is examined (Szymkiewicz 2000). The opportunity of simultaneous investigation of such flows is rather unique but such a need appears in the described case. On the one hand the gradually varied flow with negligible vertical accelerations and hydrostatic pressure distribution can be observed in some segments of water slide such as reservoirs for example. On the other one, the channel curvature, varying bottom slope, the large number of crests and contractions cause the transits between subcritical and supercritical flow which makes the flow rapidly varied and transient. In that form of flow the discontinuities, called hydraulic jumps, are often present. In the neighbourhood of those flow discontinuities the streamlines are not straight and parallel to each other and vertical accelerations cannot be omitted. In such flow conditions the pressure distribution cannot be treated as hydrostatic either.

In addition, considering the geometry of slide track, it is clear that the analysis of water flow in the 'Wide River' type object cannot be one-dimensional. Steep longitudinal and transverse bottom slopes and presence of reservoirs generally require tree-dimensional investigation.

For proper – from the practical point of view – hydraulic analysis of water slide the simulation of two-dimensional, transient and rapidly varied flow with discontinuities is necessary. At the beginning, when filling the object with water, the flow is unsteady and can resemble flood wave propagation on a dry bottom after a dam-break in the river valley. Then, due to constant inflow and outflow conditions, flow becomes steady and all local effects become stationary.

There are two ways of conducting a hydraulic analysis of an object 'Wild River' water slide: to make a physical model or to carry out the mathematical modelling. The first solution is rather expensive but it ensures the proper and effective investigation of complex flow. The other requires an appropriate adaptation of equations describing the water flow, which makes the simplifications of the complex hydraulic problem indispensable. This means, in practice, that the balance between the quality of acceptable results and the grade of considered phenomenon simplification must be ensured.

In the paper, the results of laboratory tests executed on physical model of designed water slide, installed in the Laboratory of Hydro and Environmental Engineering of the Gdańsk University of Technology, are presented. The investigations were partially financed by the 'Świat Wodny Nemo' company in Sopot.

2. Physical Modelling

In order to ensure the full similarity of phenomena in nature and the physical model the hydraulic investigations ought to be carried out preserving total hydrodynamic similarity (Cebertowicz 1958, Principles of physical modelling in hydrotechnics). For free surface water flow the equality of Froude, Euler, Reynolds and Strouhal numbers should be ensured. If the conditions mentioned are satisfied the ratio of main forces in water flow in nature and on the model are the same. However, considering the geometry of the slide and significant bottom slopes of main channels, the gravity and inertia are the dominant forces generating the water flow in the 'Wild River' object.

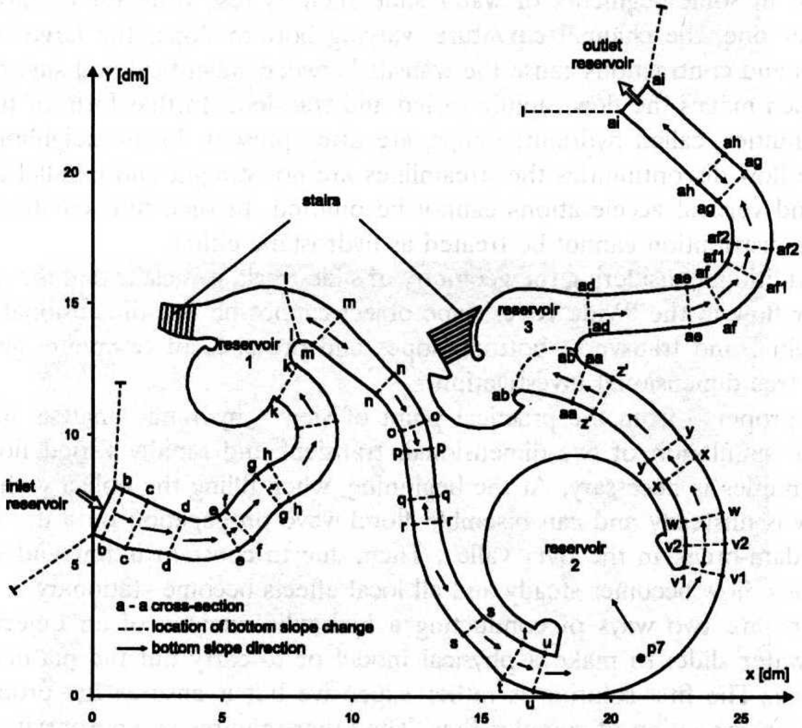

Fig. 2. Scheme of the water slide model

For hydraulic investigation of water slide the physical model in uniform scale 1:10 was built by contractor (Fig. 2). During physical modelling the real cover of channel bottom was unknown. The model made of plastic has indelible bottom of channels and reservoirs of Manning coefficient approximately equal to 0.008 $m^{-1/3}$ s. First basic tests for the given discharge proved that the supercritical flow observed in slide channels is dominant. The subcritical flow could be observed almost only inside the intermediate basins. However, turbulent flow was present in the whole object.

Considering the observation mentioned above, the most appropriate similarity criteria, which can be used to model the flow in the water slide object, seem to be the Froude and Reynolds numbers. Unfortunately, there are some difficulties in satisfying both conditions simultaneously. First of all, such an approach requires the use of two kinds of fluids differing from each other in kinematic viscosity coefficient. Because of this the physical modelling was carried out ensuring only the criterion of Froude number (Principles of physical... 1966).

The hydraulic system of the physical model was reproduced in such a manner as to ensure the consistence of inflow and outflow conditions in nature and on the model. For the given uniform linear scale $\lambda_L = 1{:}10$ the model scales of hydraulic parameters were the following (Cebertowicz 1958):

- velocity $\lambda_v = \lambda_L^{1/2}$,
- flow $\lambda_Q = \lambda_L^{5/2}$,
- time $\lambda_t = \lambda_L^{1/2}$,
- slope $\lambda_i = 1$,
- roughness $\lambda_s = \lambda_L$,
- area $\lambda_F = \lambda_L^2$.

For the given discharge $Q_r = 0.8$ m^3/s the model discharge $Q_m = \lambda_Q \cdot Q_r$ was equal to 0.0053 m^3/s. This was control on the calibrated Thompson weir. The bottom and water levels were measured using a needle water level gauge. Due to water surface oscillations the measurement accuracy was estimated to be about ±0.003 m. Local values of flow velocity were determined using a standard Prandtl tube. The task of physical tests on the slide model was to determine basic hydraulic parameters for steady flow including:

- water level along channel banks,
- location and features of the local effects such as:
  - regions of supercritical and subcritical flow,
  - hydraulic jumps,
  - water surface oblique shocks and depressions,
  - immobility (still water) zones,
  - zones of reverse flow.

The majority of phenomena mentioned cannot be determined exactly due to the considerable fluctuation of depth and velocity fields, therefore only zones of their appearance can be identified. However, the information about their location is extremely important for object designing as well as future safe operation.

3. Hydraulic Effects Accompanying the Flow

Taking into account the transient, rapidly varied flow present along the whole length of the slide track (except the reservoirs) and substantial changes in its direction (Fig. 2), the water flow in the 'Wild River' object is hydraulically very varied.

Basic phenomena accompanying the supercritical flow are, neighbouring zones of diffractions and interferences of abrupt swellings (shocks) and depressions of water surface. Such wave-type effects penetrating each nother in space are present along almost the whole length of slide channels. They often have forms similar to classic hydraulic jumps. However, typical hydraulic jumps are the result of transits from supercritical into subcritical flows, while local phenomena occurred in the flow along the slide due to significant variety of channel bend curvatures.

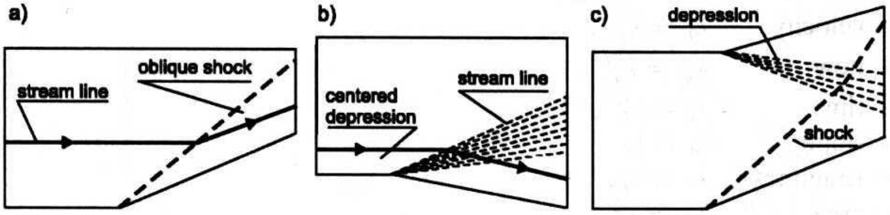

Fig. 3. Schematic local hydraulic phenomena present in supercritical flow (in plan): a) shock, b) depression, c) shock and depression (Caussson et al. 1999)

There are two basic forms of these local effects (Fig. 3):

a) oblique shock occurring near the concave corner. A sudden increase of water depth together with drop of flow velocity are present in such structures,
b) depression appearing in the neighbourhood of the convex corner. The diminishing depth of water is accompanied by increase in flow velocity.

More complex forms occurring locally are the result of superposition and penetration of phenomena mentioned (Fig. 3c). D. Causson et all. (1999) were analysing such (and other complex) structures of flow for spillway channels. For large hydraulic structures such problems were also investigated by Kubrak (1989), Morris (2000), Paguier (1995) and Szydłowski (1998).

Structures of the above-mentioned type are difficult to describe and examine in micro-scale. For that reason, in the following paper only zones of occurrence of such effects are shown. In Figure 4 (see also Table 1) these hydraulic phenomena are presented for steady flow of model discharge equal to 0.00253 m^3/s.

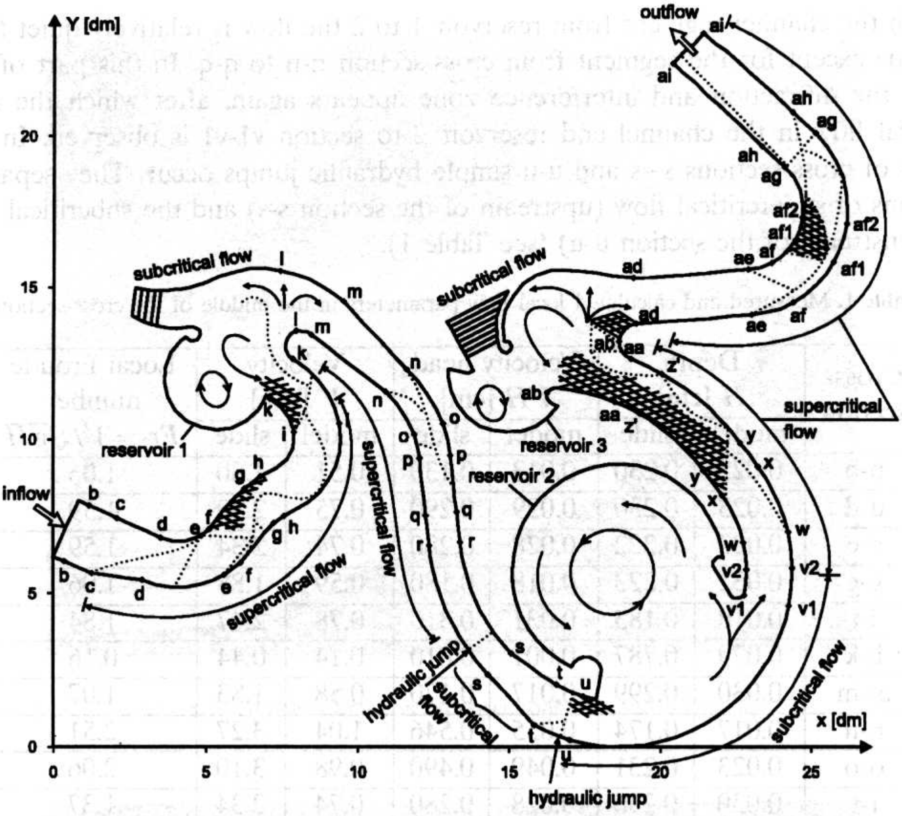

Fig. 4. Scheme of slide track with zones of local hydraulic effects: dotted line – boundaries of diffraction and interference zones, hatched region – zones of immobility and reverse flows, arrows – zones of spreading, whirls and circulation

4. Description of Flow Along the Model of the 'Wild River' Object

The flow in open channels connecting the intermediate reservoirs of water slide is supercritical. In such conditions the location, range and features of local hydraulic effects are mainly determined by bottom geometry and slide track curvature variation. The schematic illustration of the flow is shown in Figure 4. Additionally, photos in Figures 5 to 13 present the flow for selected cross-sections of the slide. Commencing from the cross-section c-c, located near the inflow reservoir, zones of diffractions and interferences of water surface shocks occur. The main stream (the greatest depths and flow velocities) is present near the right bank of the channel, therefore on the left bank the depths are small and zones of reverse flows (cross-sections e-e to h-h), as well as strong whirls in the region of abutment (cross-section k-k), can be observed.

In basins 1 and 3, similar zones of spreading as well as zones of whirls, reverse flow and circulation are visible.

In the channel segment from reservoir 1 to 2 the flow is relatively quiet (balanced) except for the segment from cross-section n-n to q-q. In this part of the slide the diffraction and interference zone appears again, after which the subcritical flow in the channel and reservoir 2 to section v1-v1 is observed. In the front of cross-sections s–s and u-u simple hydraulic jumps occur. They separate regions of supercritical flow (upstream of the section s-s) and the subcritical one (downstream of the section u-u) (see Table 1).

Table 1. Measured and calculated local flow parameters in the middle of the cross-section

Cross-section	Depth H [cm]		Velocity head VH [cm]		Velocity V [m/s]		Local Froude number
	model	slide	model	slide	model	slide	$Fr = V/\sqrt{gH}$
b-b	0.023	0.230	0.013	0.130	0.51	1.60	1.06
d-d	0.023	0.230	0.029	0.290	0.75	2.39	1.59
e-e	0.022	0.222	0.028	0.280	0.74	2.34	1.59
g-g	0.032	0.323	0.018	0.180	0.59	1.88	1.06
i-i	0.018	0.183	0.031	0.310	0.78	2.47	1.84
k-k	0.079	0.787	0.001	0.010	0.14	0.44	0.16
m-m	0.030	0.299	0.017	0.170	0.58	1.83	1.07
n-n	0.017	0.174	0.055	0.546	1.04	3.27	2.51
o-o	0.023	0.231	0.049	0.490	0.98	3.10	2.06
r-r	0.030	0.298	0.028	0.280	0.74	2.34	1.37
s-s	0.048	0.476	0.021	0.210	0.64	2.03	0.94
p7	0.043	0.430	0.003	0.030	0.24	0.77	0.37
v2-v2	0.019	0.190	0.023	0.230	0.67	2.12	1.56
y-y	0.006	0.064	0.009	0.090	0.42	1.33	1.68
ad-ad	0.030	0.295	0.018	0.180	0.59	1.88	1.10
af-af	0.006	0.058	0.069	0.690	1.16	3.68	4.88
af1-af1	0.00.3	0.030	0.084	0.840	1.28	4.06	7.48
af2-af2	0.0014	0.142	0.010	0.100	0.44	1.40	1.19
ai-ai	0.003	0.028	0.090	0.900	1.33	4.20	8.02

Due to the significant diameter and depth (1.2 m) of reservoir 2, a distinct radial flow can be observed there. This circulation is generated by the subcritical flow present in the neighbouring channel. It is clearly visible in Figure 9 corresponding to the moment of injection of marker and Figure 10 displaying the situation after full rotation of marker in the basin.

Between reservoirs 2 and 3 the slide channel has gentle bends. Almost all the water flows in the narrow zone of wave interferences extending along the right bank of channel. Commencing from the cross-section x–x to the outlet of the channel into basin 3, a wide flat zone of reverse flows occurs. Along the

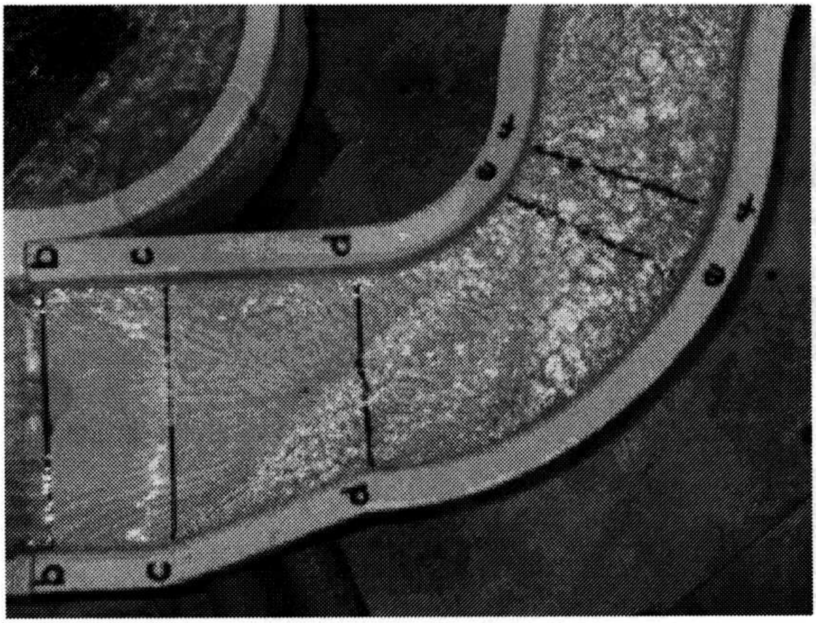

Fig. 5. Water flow between cross-sections b–b and f–f (plan)

Fig. 6. Water flow between cross-sections b–b and f–f (view)

Fig. 7. Water flow between cross-sections i–i and k–k

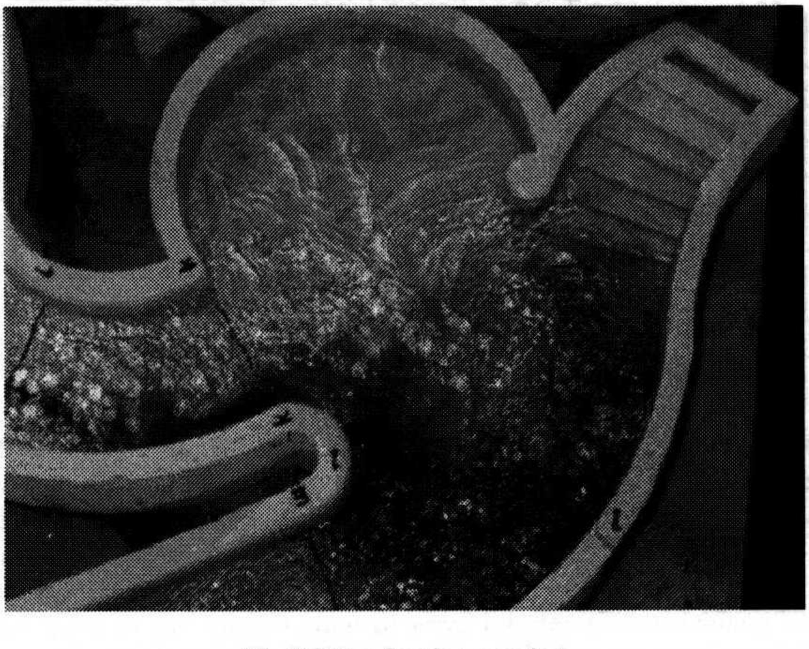

Fig. 8. Water flow in reservoir 1

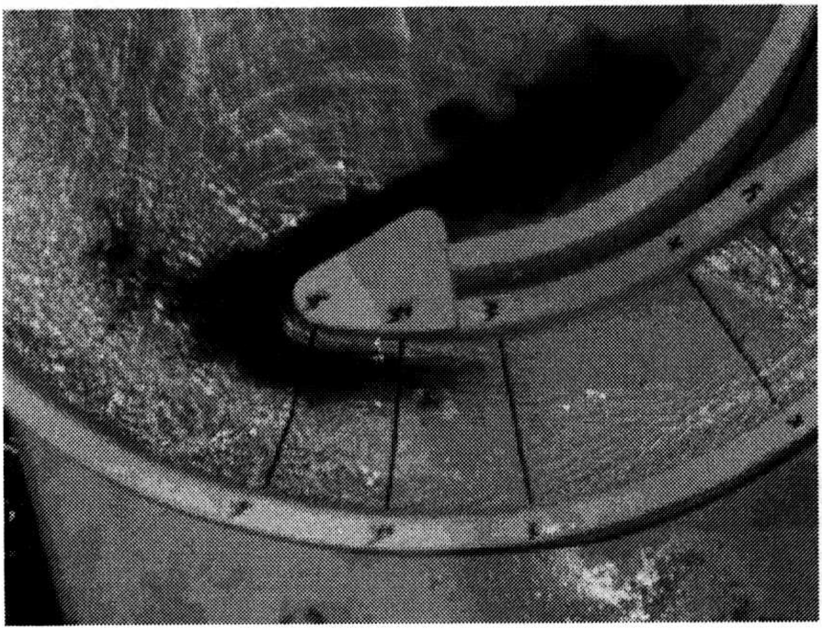

Fig. 9. Water flow between cross-sections v1–v1 and x–x

Fig. 10. Water flow in reservoir 2

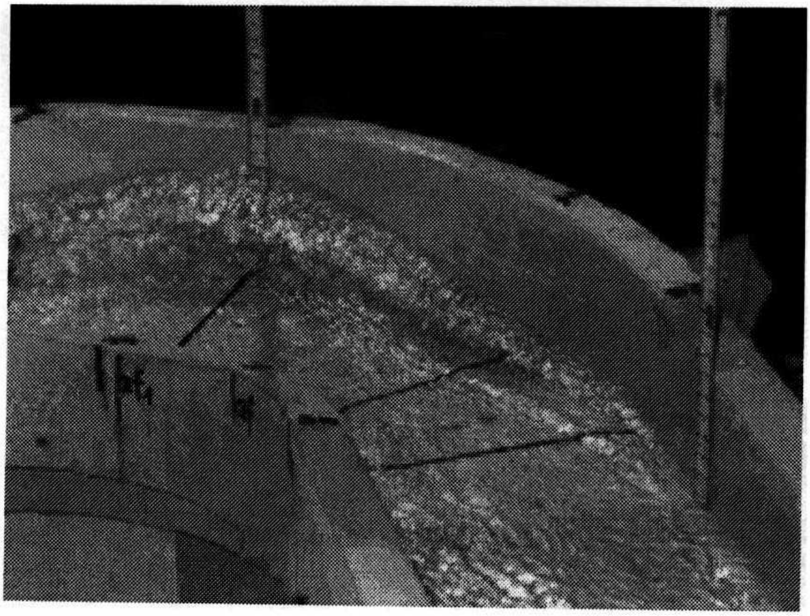

Fig. 11. Water flow between cross-sections ae–ae and af1–af1 (view)

Fig. 12. Water flow between cross-sections ae–ae and ah–ah (plan)

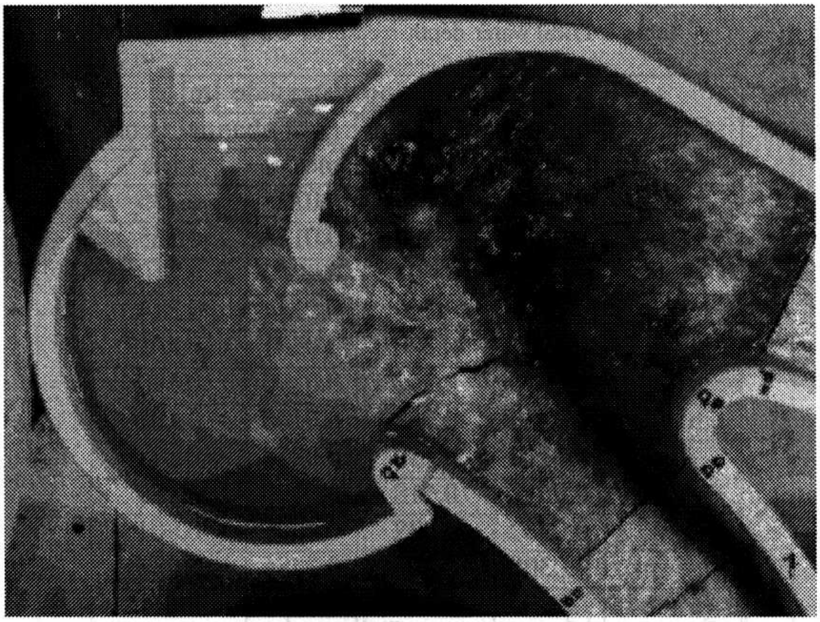

Fig. 13. Water flow in reservoir 3

last segment of the channel, ending with free outflow into terminal reservoir, interferences of water surface are present again. They are particularly visible on the sharp bend of the channel.

Moreover, they cause a strong swelling of water on the right bank of the channel with culmination between cross-sections af1-af1 and af2-af2. That situation is illustrated in Figures 11 and 12. On the left bank, a triangular (almost symmetrical) zone of reverse flow and slight depth with partially exposed bottom of the channel spreads. It is located near the left side of cross-section af1-af1.

In Figure 14 (see also Table 2) some levels of water surface along the slide channel are shown. In the cross-sections of the channels, excluding segments neighbouring on reservoirs, significant differences of water level can be observed. The depth varies there from several millimetres, as is visible e.g. in the cross-section d-d (Fig. 6 and Fig. 15a) near the initial segment of the slide, to tens millimetres in cross-section k-k near the reservoir 1 (Fig. 15c) as well as in cross-section af1-af1 on the channel bend. In nature, these values correspond to water depths of from several to tens of centimetres. That significant increasing of water depth on the right channel bank is accompanied by a relatively large flow velocity. It is equal to 1.28 m/s in the middle of the channel, which corresponds to a the velocity of over 4 m/s in nature. The Froude number is equal to 7.48. In the same cross-section, on its left-hand side, a zone of slight reverse flows and immobility spreads (Fig. 15d).

Table 2. Local water depth measured along the slide

Cross-section	Depth along waterslide [m]			
	left channel bend		right channel bend	
	model	slide	model	slide
b - b	0.0244	0.244	0.0235	0.235
c - c	0.0130	0.130	0.0165	0.165
d - d	0.0098	0.098	0.0210	0.210
e - e	0.0206	0.206	0.0344	0.344
f - f	0.0300	0.300	0.0401	0.401
g - g	0.0300	0.300	0.0190	0.190
h - h	0.0258	0.258	0.0108	0.108
i - i	0.0110	0.110	0.0277	0.277
k - k	0.0618	0.618	0.0779	0.779
l - l	0.0832	0.832	0.0801	0.801
m - m	0.0305	0.305	0.0286	0.286
n - n	0.0137	0.137	0.0211	0.211
o - o	0.0300	0.300	0.0071	0.071
p - p	0.0288	0.288	0.0310	0.310
q - q	0.0445	0.445	0.0451	0.451
r - r	0.0270	0.270	0.0308	0.308
s - s	0.0505	0.505	0.0480	0.480
t - t	0.0167	0.167	0.0215	0.215
u - u	0.0266	0.266	0.0299	0.299
v1 - v1	0.0460	0.460	0.0451	0.451
v2 - v2	0.0181	0.181	0.0232	0.232
w - w	0.0114	0.114	0.0154	0.154
x - x	0.0026	0.026	0.0314	0.314
y - y	0.0154	0.154	0.0344	0.344
z' - z'	0.0153	0.153	0.0216	0.216
aa - aa	0.0192	0.192	0.0322	0.322
ab - ab	0.0777	0.777	0.0658	0.658
ad - ad	0.0296	0.296	0.0362	0.362
ae - ae	0.0126	0.126	0.0113	0.113
af - af	0.0035	0.035	0.0294	0.294
af1 - af1	0.0046	0.046	0.0508	0.508
af2 - af2	0.0072	0.072	0.0309	0.309
ag - ag	0.0055	0.055	0.0305	0.305
ah - ah	0.0032	0.032	0.0138	0.138
ai - ai	0.0106	0.106	0.0028	0.028

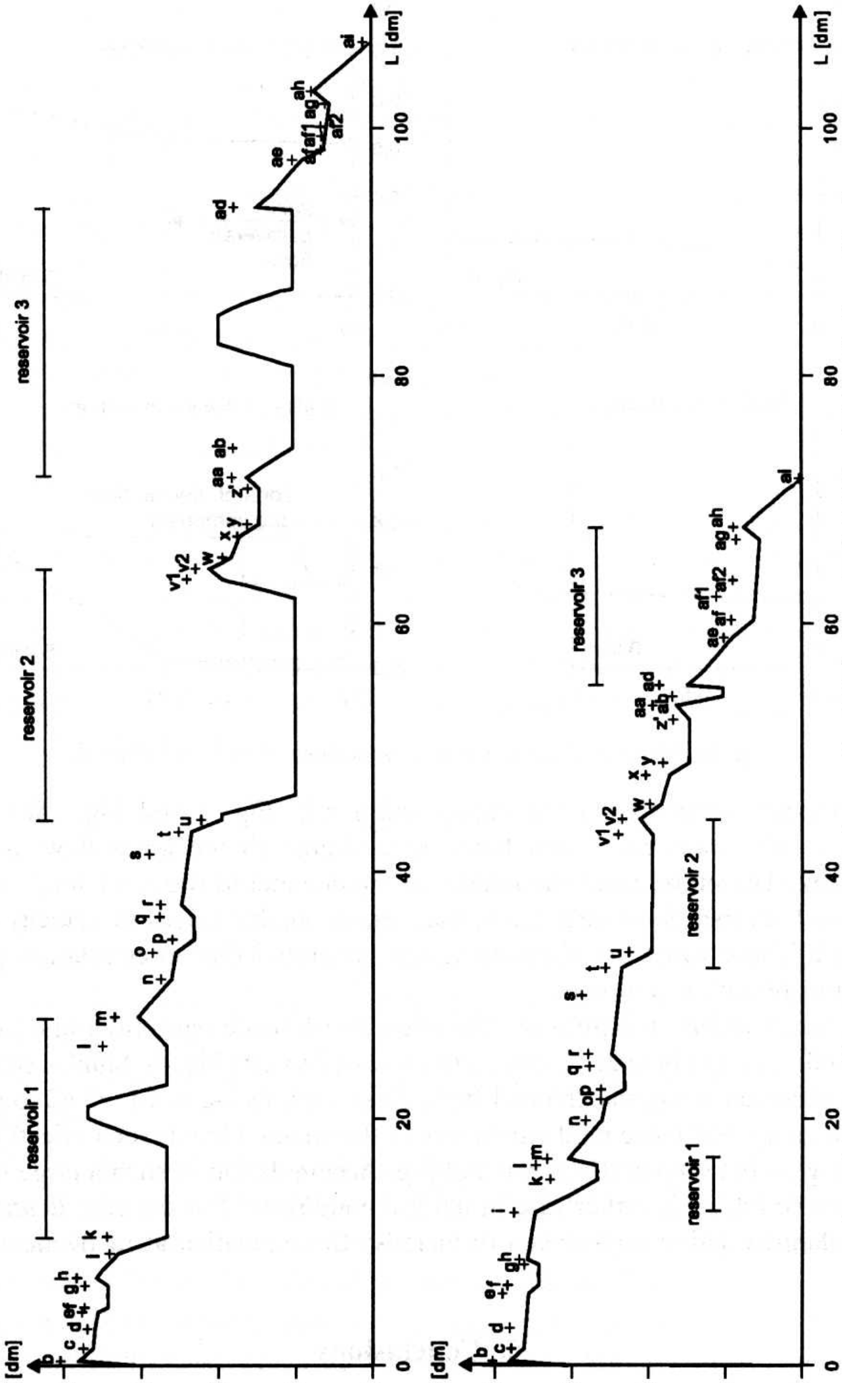

Fig. 14. Channel bottom (–) and measured local water level (+) along the left (a) and right (b) channel bank

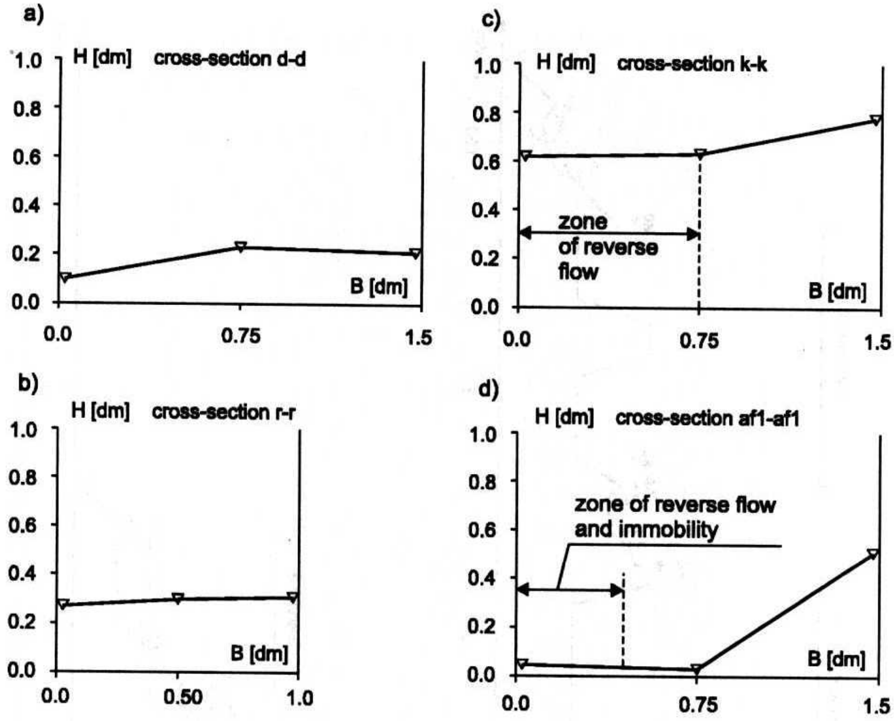

Fig. 15. Water level measured in cross-sections of the slide channel

It appears otherwise in the cross-section k-k (Fig. 7 and Fig. 15c), where despite a mild transverse water head slope almost all the water flows near the right bank. Therefore, from the middle of the channel to the left bank, a zone of whirls and reverse flows extends. In that region similar values of velocity can be observed. These hydraulic phenomena are generated due to circulation present in the neighbouring reservoir.

Distinctly visible structures of diffraction-interference types (a) and (c) occurrs in the slide channel between cross-sections v2–v2 to ź-ź (Fig. 4). Similar structures can be observed along the channel from cross-sections c-c to f-f, v2-v2 to y-y and ae-ae to ag-ag. For more mild curvatures of the channel bends such effects appear in the region between sections n-n and p-p. Accumulation of such a large number of hydraulic effects is rather rare in natural conditions. For the case described, it was a planned action undertaken to increase the recreative attractiveness of the object.

5. Conclusions

In the paper, the results of physical modelling of the flow within the 'Wild River' type water slide have been presented. The water flow observed in the slide can be defined as transient and rapidly varying. The flows changed from supercritical in channels to subcritical appearing in the intermediate reservoirs. Large numbers of local hydraulic effects of a complicated, discontinuous nature were observed in the object. The different kinds of flow and hydraulic phenomena are the result of designed slide track geometry with strongly varying bottom slopes and curvatures of channel bends.

Unfortunately, in the water slide designing process, there are no simple instruments to make the analysis of complex hydraulic phenomena for the assumed geometry of the slide track possible.

Model investigations are relatively expensive, but they can solve basic hydraulic problems, i.e. determination of water depth in channels and reservoirs, flow velocity, zones of whirls and immobility, which are important for safe operats of object. However, this kind of analysis is difficult to adapt for varying design conceptions, which is one of the disadvantages of physical modelling.

For that reason, a separate paper, containing description of mathematical model of flow in water slide together with its numerical application for 'Wilde River' object, will be presented in the future. The model will be based on equations of unsteady, gradually varied free surface water flow. In the model, the internal structure of hydraulic discontinuities will be omitted and hydraulic jumps will be defined as single discontinuities. If the shallow water flow equations in conservative form are used, the model can be adapted to simulate the transient, rapidly varied flow problem.

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