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Investigation of a Slotted Separator for Hydromechanical Installation of Sludge Removal from a Water Reservoir

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1. Introduction

The gradual silting of reservoirs, causing their capacity reduction, is a crucial factor limiting their proper operation. In the summary of the KLIMAT project (Kloze & Sieinski 2012), it was assessed that the large retention reservoirs existing in Poland lost over 200 million m^3 of their original capacity. It was found that in Poland there is no full, reliable information about the current capacity of dam reservoirs. This was supported by the analysis of data from 51 reservoirs, of which only on one measurement were carried out every 6 years, on 21 bathymetric measurement reservoirs were never performed, and on the other controls were carried out every 5-10 years or with breaks from 23 to 45 years. There are no systematic studies of smaller reservoirs that are more sensitive to capacity loss. The silting intensity of reservoirs, expressed in terms of the average annual reduction in their initial capacity, is for large reservoirs around 0.25%, for mediums around 0.5%, and for small ones even up to 3% (Madeyski et al. 2008). Michalec (2012) on the basis of research suggests that the function of small water reservoirs is limited already by reducing the volume from 40 to 60% and therefore the service life of these reservoirs should be determined for silting of 50% of primary capacity.

The operating costs associated with the removal of sludge usually exceed the investment costs for the construction of a new reservoir.

However, the possibility of locating and building large capacity reservoirs in Poland are significantly limited and therefore the degradation of existing reservoirs cannot be allowed (Kloze & Sieinski 2012).

Despite the recommendations of the EU Water Framework Directive (2000), to achieve good state and ecological potential of surface water by the end of 2015, more than half of these waters (including 90% of lakes) have not achieved this goal. One of the most important reasons for this ecological state of Polish waters is the accumulation of organic fractions of bottom sediments, which, by fermenting, emit soluble phosphorus compounds to the water body and extract oxygen. This leads to eutrophication and algal blooms that dies and fall massively to the bottom of the reservoirs.

The construction of a dam on the river interrupts the continuity of the flow of river sediment. Conditions are created for the development of undesirable processes: accumulation of sediment, decrease of useful capacity of the reservoir, rising of the bottom and level of water in the backwater of the reservoir, and erosion of the bottom and banks below.

One of many methods of revitalizing small water bodies is the removal of bottom sediments accumulated over the years, for example by leaching or periodically dredging sediments (Bartoszek et al. 2017). These works require the use of pumps with combustion engines, although the energy of accumulated water can be used to rinse the sediments from the reservoir (Zawadzki et al. 2017).

2. Installation of hydromechanical sludge removal

Morris & Fan (1997) proposed that in order to reduce the volume of accumulated sediment and leaching accumulated deposits, use the ducts laid on the bottom or floating on the surface and carried through the dam as a siphon or antisiphon. The technique has been successfully implemented and described by Liu et al. (2002) and Carone et al. (2006). The material transported in this way can flow directly to the river or fields. The debris entering the reservoir can be continuously or periodically transported from the inlet, upper part of the reservoir to the lower station by means of ducts arranged on the bottom (Morris & Fan 1997).

Zawadzki & Błażejewski (2017) developed a prototype installation that would allow sorting of transported sediments, of which thicker mineral debris is directed to the river, below the strengthening of the bottom and minor mineral and organic fractions, after dewatering could be used for agricultural purposes. The installation guarantees continuous flow of water and sediment, and the use of only the difference between the upper and lower water levels. This installation has been described in the patent application and then covered by patent protection (decision of November 2017).

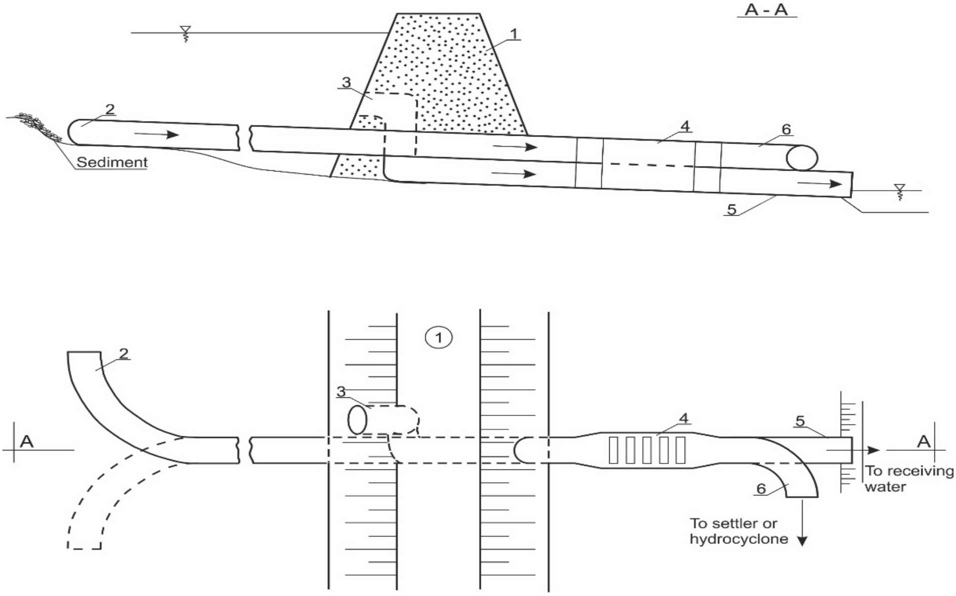

Fig. 1. Scheme of installation for hydromechanical sorting and removal of sediments (Zawadzki & Błażejewski 2017)
Rys. 1. Schemat instalacji hydromechanicznego sortowania i usuwania osadów dennych (Zawadzki i Błażejewski 2017)

The installation consists of two pipes, connected partly on a short section by a slot separator (4). The inlet to the pipe to which the sludge is sucked together with the water (2) is located in the reservoir upstream the dam (1). The second pipe (3) is used to extract pure water. In the separator (4), the thicker mineral material falls through the slots into the lower duct (5), which along with the clean water is transported directly to channel downstream of weir. Water carrying organic and fine mineral material, flowing above the slots, is guided by a pipe (6) to the hydrocyclone.

3. Slotted separator

The most important element of the hydromechanic installation for removing and purifying the bottom sediments is the slit separator, which is to separate the sediment collected from the bottom of the reservoir into two fractions. The operation of the separator is modeled on the work of a slotted sandbox, which is a horizontal flow device with a separate sand storage chamber outside the flow channel (Mołoniewicz et al. 1979, Cywiński et al. 1972). This sand is removed periodically mechanically or hydraulically. In the separator, continuous flow of water or water with sediments in the line below the slots is to ensure the transport of solid particles. The construction and operation of the separator should be carried out in such a way as to create working conditions in which:

- at least 75% of the mineral parts with a diameter of more than 0,2 mm are retained,
- organic particles more than 10% of the total amount of transported sediment should not be retained (Mołoniewicz et al. 1979).

The principle of operation of this type of separators is that as a result of the flow velocity reduction, a thicker fraction (sand) is released from the transported mixture, which is dragged through the bottom into the slots. According to Hazen's theory, the time t of a solid particle falling with the velocity $w \approx w_{ss}$ at the depth h is equal to the time of its horizontal transport to the distance $l = t \cdot v$. The velocity of the water flow in the separator v should depend on the settling velocity of the solid particle, the removal of which is desirable. The calculation parameters of horizontal channel separators are: flow velocity, flow time and hydraulic load on the surface of the grit chamber.

For the proper operation of the separator, it is necessary to create heterogeneous flow conditions or, possibly, a flow with a movable bottom (the highest concentration of solid particles is at the bottom of the duct). Assuming that in the water supply line with sediments to the slotted separator, the flow will be in a homo- or heterogeneous regime, at the beginning of the separator a velocity should be reduced to approx. $0.4\ m \cdot s^{-1}$ or $0.7\ m \cdot s^{-1}$ (Mołoniewicz et al. 1979). These velocities allow to stop sand with a diameter of 0.2 mm or 1.0 mm.

When separating mixtures of fine and very fine grains, the classification process (separation) is often carried out in a water or air medium, and different forces act on the grain of the classified material (centrifugal, jet or center resistance, gravity, buoyancy, etc.). it is not perfect and part of the grain goes to the wrong product.

Theoretically, a perfectly working slotted separator should allow the separation of two factions: thicker (cleaned), after passing through the slots flowing down the lower duct, from finer (polluting), discharged with the upper duct. An undesirable effect would be the mutual contamination of the fraction after passing through the separator slots. In our research, it was proposed that the efficiency of the dispersive suspension separator should be calculated according to the formula:

$$\eta = \beta_p \cdot (1 - \beta_n) \quad (1)$$

where:
β_p – degree of sorting desired grains,
β_n – degree of sorting unwanted grains.

The definition of degree of sorting β was adopted after Kowalski (2004), which, with the degree of sedimentation (or degree of deposition) of the *i*-th grain class, determines the ratio of the mass stream of particles in the nozzle to the associated stream in the suspension introduced into the plant (in the feed). The degree of sorting informs what part of the grains of the *i*-th fraction transported by the upper duct flows along with the water through the fissures to the lower duct. It is excepted that in a well-functioning separator the degree of sorting of the thicker factions will be as high as possible ($\beta_p \rightarrow 1$), while for the fine and organic fractions, the smallest ($\beta_n \rightarrow 0$).

4. Laboratory tests

In order to determine the hydraulic conditions for the flow and sorting of the mixture of water and sand through a slotted separator, laboratory tests were carried out. The research installation was made at the water laboratory of the Department of Hydraulic and Sanitary Engineering, Poznan University of Life Sciences. The laboratory installation consisted of a supply pipeline, a sediment feeder, a slotted separator and two discharge pipes with valves (Fig. 2). The installation allow to measure and regulate flows in the upper and lower separator ducts.

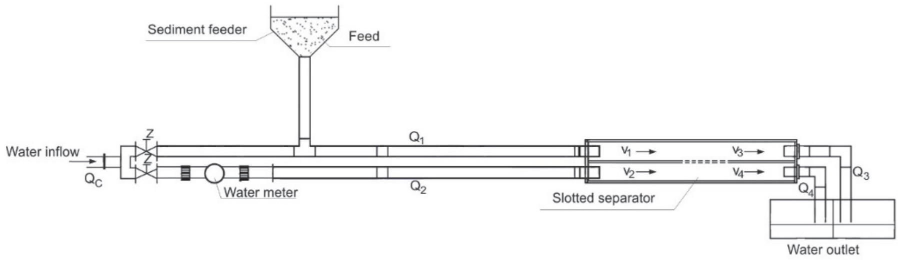

Fig. 2. Scheme of laboratory installation (own work)
Rys. 2. Schemat instalacji badawczej (opracowanie własne)

The slotted separator was made as a rectangular box with external dimensions: length 1020 mm, height 210 mm and width 100 mm. In the middle of the rectangular height, guides were made to install a baffle plate dividing the separator into working chambers with square cross-sections and dimensions of 80 x 80 mm. The cuboid was closed with front and back panels, in which two 50 mm diameter holes were made, allowing for supply and drainage of the water jet from the upper and lower separator wire. To enable observation of the processes taking place in the separator, all of its elements are made of transparent polymer plastic with a thickness of 10 mm. This resulted in a rigid and airtight installation, not subject to deformation under the influence of water pressure and the weight of the mixtures.

The tests on the physical model were conducted under steady state conditions, with total flows (flow fed to the research installation $Q_c = Q_1 + Q_2$) taken from the range of 3.50 $dm^3 \cdot s^{-1} < Q_c <$ 12.50 $dm^3 \cdot s^{-1}$. The assumed flow rates allowed to obtain the average water flow rates at which hydraulic separation of solid particles was possible.

In the separator, 3 slots with a width of 20 mm were chosen every 20 mm (spacing between the axis of the slots - 40 mm). A larger number (14 or 9) of slots meant that most of the mineral material fed to the separator through the upper duct, flows through the slots and flows out through the bottom duct of the separator. It was assumed that the first slot should not be less than 0.5 m (half the length of the separator) and that this length allows the thicker mineral fractions to sink to the bottom of the sandbox and transport the particles in the bedloaded regime.

In the first stage of the research, as a mineral material, simulating the transported sludge, three mineral fractions with grains were used: from 0.125 mm to 0.5 mm, from 1.0 mm to 2.0 mm and from 4 mm to 20 mm. The fractions were obtained after sieving a sand. However, the results of the tests were not entirely satisfactory. During the tests, hydraulic conditions were created at which sorting of transported fractions took place and relatively high efficiency of the separator was achieved (maximum η = 51%, average efficiency of the separator ranged from 32% to 0.35%). Higher efficiency of the separator was obtained for similar velocities in the upper and lower ducts ($v_1 \approx v_2$). The other velocity ratio on the inflow ($v_1 \ll v_2$ or $v_1 \gg v_2$) caused unfavorable hydraulic conditions for grain sorting.

Observation of transported mineral particles of different density and shape (which could have a significant influence on the transport of individual grains, Bridge & Bennett 1992, Hämmerling et al. 2014), does not allow assuming in the analysis the assumption that all fraction grains have equal density (ρ_s = 2650 kg· m^{-3}), a spherical shape described by d_s diameter as well as described by one value of the settling velocity w_{ss} of a single grain.

Therefore, in main studies, spherical particles of different density were used as the simulation material for the removed sediment. The balls were used - ASG ammunition (Air Soft Gun) for pneumatic guns, which manufacturers guarantee high accuracy (diameter 6.0 ± 0.05 mm), and which is made of plastics of various density and different color (Fig. 3). Particles with specific gravity ρ_s = 1061, 1768 and 2653 kg·m^{-3} were used. Their detailed characteristics are presented in Table 1.

Two series of experiments were performed: **A** with spherical particles K^{I} and K^{III} and **B** with K^{II} and K^{III}. In experiment **A**, particles with a large difference in density were deliberately selected so that favorable hydraulic sorting conditions and high efficiency of the separator η (eq. 1) were obtained. In all experiments, the equal velocity at which water was supplied to the separator by the upper and lower lines $v_1 = v_2$ was assumed. In subsequent repetitions, the flow rate was increased so that the velocity v_1 were equal 0.4 m·s^{-1}, 0.45 m·s^{-1}, 0.5 m·s^{-1} and 0.55 m·s^{-1} on the inflow. Dosing of solid particles was started after the water flow conditions were established. The experiments at four different velocities v_1 were carried out with a total mass of dosed particulates (feed) equal to: 400 g, 600 g and 1000 g (Tab. 2). Each experiment at a given average velocity and feed was repeated three times, performing a total of 36 experiments in each series. The results of experiments in series **A** and **B** of the studies are shown in Figures 4-6.

Fig. 3. The material used in the research. Spherical particles with diameter d = 6.0 ± 0.05 mm and specific density ρ_s = 1061, 1768 and 2653 kg·m^{-3}
Rys. 3. Materiał użyty w badaniach. Cząstki kuliste o średnicy *d* = 6,0 ± 0,05 mm i gęstości właściwej ρ_s = 1061, 1768 i 2653 kg·m^{-3}

Table 1. Hydraulic characteristics of spherical particles
Tabela 1. Charakterystyka hydrauliczna cząstek kulistych

Symbol	Specific density ρ_s	Mass	Drag coefficient C_D	Reynolds number for grain Re_s	Settling velocity w_{ss}
	kg·m^{-3}	g	–	–	m·s^{-1}
K I	1061	0,12	0,571	545	0,092
K II	1768	0,20	0,415	2273	0,381
K III	2653	0,30	0,388	3447	0,578

Fig. 4 shows the degree of sorting and separator efficiency in subsequent **A**-series experiments. In these experiments the separation of particles of different density was relatively easy and effective. At the bottom of the separator from the separator, almost only K^{III} particles and few K^{I} were observed. This is confirmed by degree of sorting β (eq.1): very high 0.75-0.95 for K^{III} particles falling through the slots and very low 0.0-0.15 for K^{I} particles.

Table 2. The volume flow of solid particles Q_s during emptying of the feeder
Tabela 2. Objętościowe natężenie cząstek stałych Q_s przy wypływie z dozownika

Mixture	Feed mass	Volume of solid particles V_s	Average dispensing time $\bar{t}_s$	Volume flow of solid particles [1] Q_s
	g	dm^3	s	$dm^3 \cdot s^{-1}$
$K^I + K^{III}$	200+200	0,264	7,3	0,036
	300+300	0,396	10,9	0,036
	500+500	0,660	18,6	0,035
$K^{II} + K^{III}$	200+200	0,189	5,5	0,034
	300+300	0,283	7,8	0,036
	500+500	0,471	13,8	0,034

[1] volume flow of solid particles determined on the basis of $Q_s = \frac{V_s}{\bar{t}_s}$

In the **B** series experiments, the efficiency of the separator varied from 0.1 to 0.4 (Fig. 5) and was significantly lower than in the **A** series experiments. Although the degree of K^{III} particle sorting remained very high (β_p = 0.78-0.91) but at the same time too many K^{II} particles were flowing through the slots (β_n = 0.53-0.85). If for Mołoniewicz et al. (1979) criteria for evaluating the correct operation of the separator will be adopted (no less than 75% of the initial mass of the coarse fraction is retained, and the admixture of fine fraction – undesirable – does not exceed 10%). The expected efficiency should not be less than: $\eta = 0.75 \cdot (1-0.1) \cdot 100\% = 67.5\%$. In the **A** series experiments, higher efficiency of the separator was obtained.

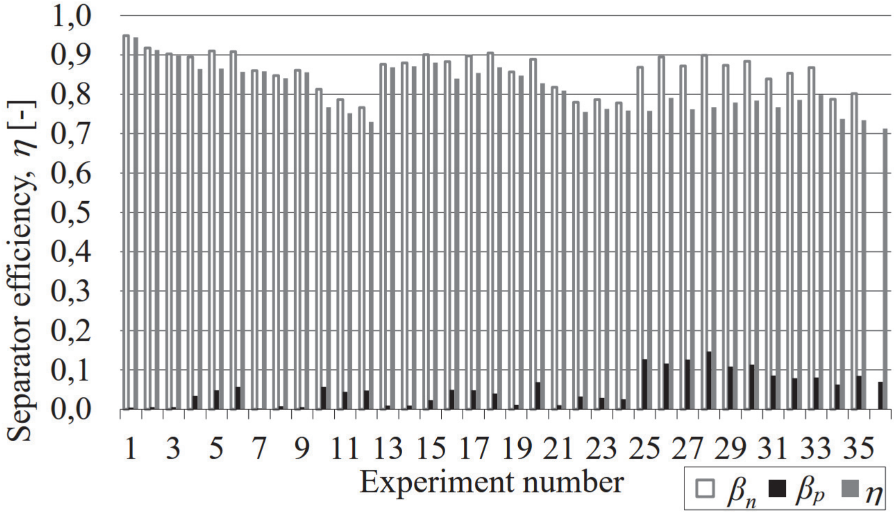

Fig. 4. Variations in degree of sorting and efficiency in subsequent experiments in series **A**
Rys. 4. Zmiany stopnia wysortowania i sprawności w kolejnych doświadczeniach serii **A**

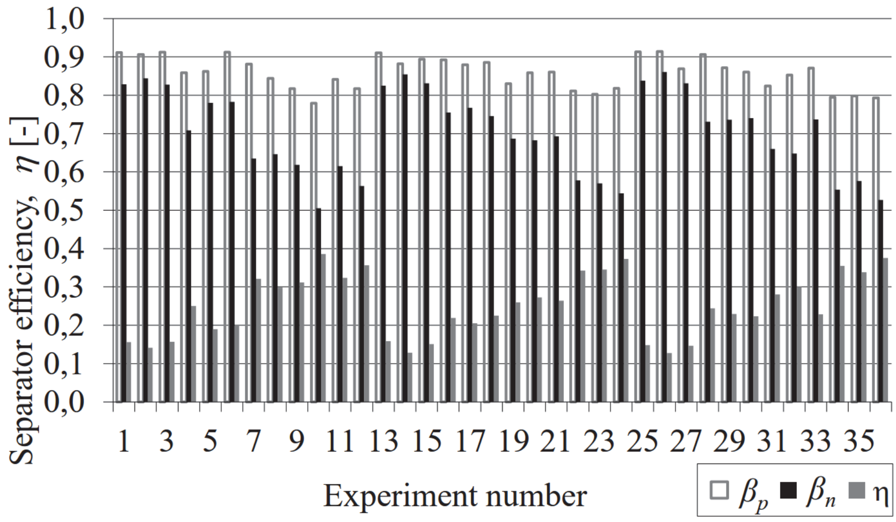

Fig. 5. Variations in degree of sorting and efficiency in subsequent experiments in series **B**
Rys. 5. Zmiany stopni wysortowania i sprawności w kolejnych doświadczeniach serii **B**

In experimental **A** the efficiency of the separator was not less than 70%, the highest was obtained with the velocity v_1 = 0.4 m·s^{-1} and the feed 400 g η = 0.9-0.95, the smallest at v_1 = 0.55 m·s^{-1} and feed 1000 g η = 0.7-0.75. It can be noticed that the efficiency of the separator decreased not only with the increase in the weight of the feed, but also with the increase in velocity v_1 (Fig. 6).

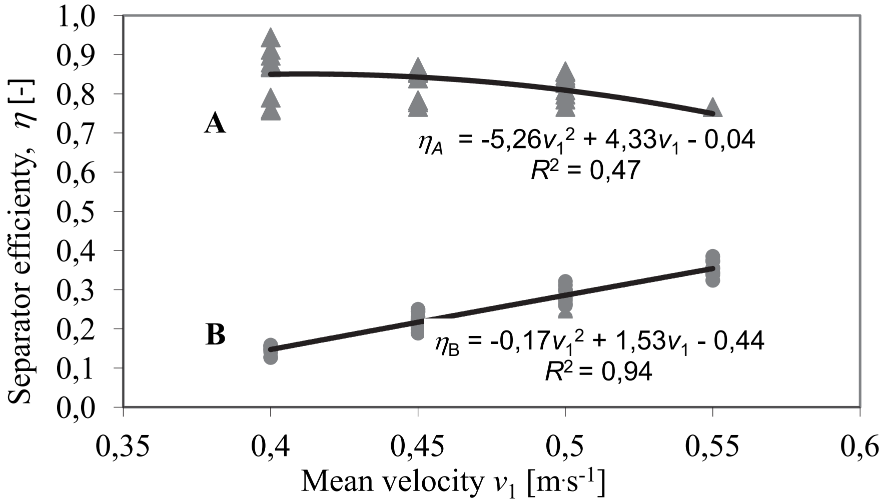

Fig. 6. Relationship between average approach velocity v_1 and separator efficiency in experiment of series **A** and **B**
Rys. 6. Zależność miedzy prędkością średnią v_1, stopniem wysortowania i sprawnością separatora w doświadczeniach serii **A i B**

Efficiency η significantly improved with the increase of the flow rate of the mixtures the upper separator line above the slots (Fig. 6). The value of the determination coefficient R^2 = 0.94 indicates a very strong relationship (R^2 > 0.9) between these values. The increase in velocity $v_1$caused that a larger number of K^{II} particles did not roll over the bottom, but was carried over the slots and the sorting was more effective.

The increase in velocity in the upper duct above the v_1 slots in the **A** series experiments caused a slight decrease, and in the **B** series experiments a significant increase in the efficiency of the separator. Hydraulic conditions have an effect on the sludge flow regime, in this case in particular on lighter K^{I} or K^{II} particles. Fig. 7 shows the dependence of the sorting degree β and the velocity ratio in the upper conduit above the slots v_1 to the hydraulic feature of the w_{ss} particle. The value of the coefficient of determination shows a very strong relationship between these values. Variability of the degree of sorting in almost 90% is caused by changes in the relation of the average velocity and hydraulic characteristics of the grain (settling velocity). At velocities $v_1 >> w_{ss}$, the particles are transferred above the slots.

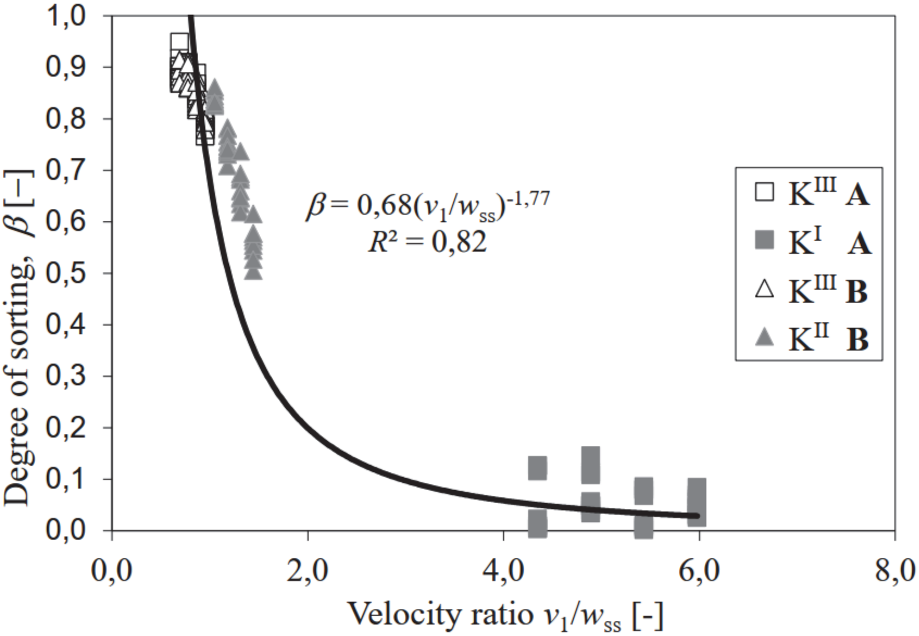

Fig. 7. Relationship between v_1/w_{ss} and degree of sorting β
Rys. 7. Zależność między v_1/w_{ss} i stopniem wysortowania β

The second parameter that can affect the efficiency of the separator is the area of the working chamber, determined to the edge of the last slot. As mentioned earlier, the work of a slotted separator is similar to the operation of a settling tank with continuous removal of deposits. According to Hazen's law, the efficiency of sedimentation of a free falling particle depends only on the surface of the settler, and the depth of the settler has not influence (Cywiński et al. 1972). Unfortunately, in the described tests, an attempt to change the position configuration, spacing and the number of slots was unsuccessful. Although in the initial phase of the research (with mineral particles) the position and number of slots were changed, but after a series of experiments with 3 slots with 2 cm intervals, it was not possible to change the configuration of the slots.

The values determining the efficiency of the slotted separator can be taken into account by assuming the dimensionless Hazen number expressed in the formula for analysis

$$Ha = \frac{Q}{A_o \cdot w_{ss}} = \frac{v_1 \cdot A}{A_o \cdot w_{ss}} = \frac{v_1}{w_{ss}} \cdot \frac{A}{A_o} \tag{2}$$

where:
Q – volumetric flow rate, $m^3 \cdot s^{-1}$,
A_o – surface area of the horizontal projection of the settling chamber, m^2,
w_{ss} – settling velocity of single particle, $m \cdot s^{-1}$,
v_1 – average velocity, $m \cdot s^{-1}$,
A – cross-sectional area of the working chamber, m^2.

Fenner & Tyack (1997) and Gulliver et al. (2009) as the similarity criteria for hydrodynamic separators, they propose Hazen number:

$$Ha = idem \tag{3}$$

Accepting the Hazen number as a similarity criterion allows for planning subsequent laboratory tests, designing an installation for drowning water reservoirs in a technical scale or forecasting the efficiency of geometrically similar slot separators. Considering the Hazen number, when modeling geometrically similar separators and using the same size particles $(w_{ss})_M = (w_{ss})_{M\alpha}$ we calculate the volumetric flow rate of water according to the dependence

$$\frac{Q_{M\alpha}}{Q_M} = \frac{(w_{ss} \cdot A_o)_{M\alpha}}{(w_{ss} \cdot A_o)_M} = 1 \cdot \alpha^2 = \alpha^2 \tag{4}$$

where:
α – scale ratio.

The fulfillment of this condition causes that on geometrically similar separators, its dimensions can be changed: width, number and spacing of slots, assuming the average flow velocity and the ratio v_1/w_{ss}, at which the process was the most efficient.

5. Conclusions

Laboratory tests were carried out on a physical model of a slotted separator, in which mineral particles with diameters from 0.15 to12.0 mm and spherical particles with a diameter of 6.0 mm made of materials with a density range from 1000 to 2650 kg·m^{-3}. The tests have shown that it is possible to create hydraulic conditions when the sediments are separated into two fractions and their further transport by means of two pipes. It allows to separate thicker mineral fractions of sediments (gravel, coarse and medium sand) from organic impurities and finer mineral fractions in the form of a slurry. The relations between the average water flow velocity above the slots and the settling velocity of particles were significant.

Laboratory tests also showed various structural defects of the slotted separator, affecting turbulence of flow (rapid changes in cross-section), as well as the efficiency of its work.

In laboratory tests, the diameters of pipes supplying mixture or water were equal to 0.05 m. Installation with such dimensions can be used in practice, but it can be pipes with larger diameters. It can be expected that installations that are geometrically two, five or ten times larger, in proportion to the increase in volume flow of water, will be able to remove many times more deposits from the bottom of the reservoir.

It has been assumed that the Hazen number is a good criterion for hydrodynamic similarity and allows the design of separators several times larger and forecasting the effectiveness of their work or the determination of the characteristic diameters of the separated sediment. This number takes into account both the variability of the velocity ratio v_1/ w_{ss} and the change in the area of separator, resulting from different widths, spacing and number of slots.

The prototype installation on a technical scale will be examined in field condition and financed by the "Incubator of Innovation +" project, co-financed from funds for learning under the non-competition project

"Support for management of research and commercialization of R & D results in scientific units and enterprises", implemented in under the Intelligent Development Operational Program 2014-2020 (Measure 4.4).

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Badania separatora szczelinowego instalacji hydromechanicznego usuwania osadów ze zbiornika wodnego

Streszczenie

Zamulanie zbiorników wodnych w Polsce postępuje w tempie 0,5-5% pojemności rocznie, stąd niezbędne są działania w kierunku ograniczenia tego niekorzystnego zjawiska, m. in. poprzez odmulanie. Stosunkowo tanią i wydajną metodą usuwania osadów ze zbiorników jest zasysanie uwodnionych osadów przez syfon lub lewar, wyposażony dodatkowo w separator cząstek stałych. Zadaniem prototypowej instalacji do hydromechanicznego usuwania i oczyszczania osadów jest rozdzielenie osadów pobieranych z dna zbiornika na dwa strumienie, zawierające: frakcje grube (pożądane), kierowane bezpośrednio do rzeki poniżej piętrzenia, oraz frakcje drobniejsze i lżejsze (niepożądane), które po odwodnieniu mogą być wykorzystane, np. rolniczo. Wysortowane grube frakcje mineralne ograniczają erozję koryta cieku poniżej zbiornika.

Przeprowadzono badania laboratoryjne na modelu fizycznym separatora szczelinowego, w których użyto cząstek mineralnych o średnicach 0,15-12,0 mm oraz cząstek kulistych o średnicy 6,0 mm, wykonanych z materiałów o gęstości od 1000-2650 kg·m^{-3}. Badania wykazały, że jest możliwe stworzenie takich warunków hydraulicznych, w których zachodzi rozdzielenie osadów na dwie frakcje i ich dalszy transport dwoma przewodami. Istotne okazały się relacje prędkości przepływu hydromieszaniny powyżej szczelin do prędkości opadania ziaren.

Abstract

The siltation of water reservoirs in Poland is progressing at the rate of 0.5-5% of capacity per year, hence the actions necessary to limit this unfavorable phenomenon are necessary, among others through desludging. A relatively cheap and efficient method of removing sediments from reservoirs is sucking in hydrated sludge through siphon or antisiphon, additionally equipped with a solid particle separator. The task of the prototype installation for hydromechanical removal and purification of sediments is the separation of sediments collected from the bottom of the reservoir into two streams, containing: coarse fractions (desirable), directed directly to the river below the damming, and finer and lighter (undesired) fractions that can be used after dehydration), e.g., agricultural. Sorted thick mineral fractions limit the erosion of the channel of the watercourse below the reservoir.

Laboratory tests were carried out on a physical model of a slotted separator, in which mineral particles with diameters of 0.15-12.0 mm and spherical particles with a diameter of 6.0 mm were used, made of materials with a density of 1000-2650 kg·m^{-3}. The tests have shown that it is possible to create hydraulic conditions in which the sediments are separated into two fractions and their further transport by means of two pipes. The relations between the velocity of the water flow above the slits and the velocity at which the grains descended were significant.

Słowa kluczowe:
zbiornik wodny, sedymentacja, odmulanie, zasysanie osadów, separator szczelinowy

Keywords:
water reservoir, sedimentation, desilting, sediment hydrosuction, slotted separator