PAP-826

REMOVAL OF SEDIMENT PARTICLES BY VORTEX BASIN

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Mashauri, A. 1983. Removal of sediment particles by vortex basin. Aqua Fennica 13: 27–33.

This paper discusses the hydraulic performance of vortex-type settling basins – both, with horizontal and sloping floor – in the sediment removal problem for water treatment intakes, hydropower plants and irrigation schemes. The theoretical equations governing the dominant flow movement and eventual sedimentation of particles are summarized to highlight the background theory overlaying the performance of the basin with horizontal floor. Parameters such as angular velocity, ω; the vorticity force, C; the settling efficiency, η ; are determined as functions of the inflow discharge, Q_i, orifice diameter, D_o, and its ratio to the basin diameter, D/D_o and the particle size D_s. The results, settling efficiency η , and amount of water through orifice Q_o, are given for both versions – horizontal floor and sloping floor – and they show a respectable performance. Settling efficiency is well above $\eta = 80$ % for particles as small as 0.125 mm in diameter. The amount of water Q_o, through the orifice hardly exceeds 15 % of the inflow discharge Q_i. The vortex-type settling basin can therefore be used for sediment removal with high efficiency for irrigation, water treatment and hydropower plants.

Index words: sediment removal, vortex basin, settling basin.

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INTRODUCTION

General

Design of settling basins in the field of water treatment, hydropower plants and irrigation has developed very much in the last decade and continues to be refined (Camp 1946, 1953). However, in most cases than not, the basins are usually designed to settle particles and flocs from flocculated waters (especially in drinkable water treatment plants (Cecen 1977)) which adds to the economic burden of the whole treatment exercise due to chemical inputs, dosing equipment and mixing facilities. With this in mind it is therefore necessary to design a basin which will perform the particle settling, with a high degree of removal, without any chemical inputs (Mashauri 1981).

The vortex-type settling basin wh[illegible] is essentially a "bath tub" with a central orifice to discharge settled particles has been developed, experimented and the results obtained (Cecen and Akmandor 1973) show the potentiability of its use in the intakes for water treatment works, hydropower plants and irrigation schemes. The model study was designed and a physical model constructed in the hydraulic laboratories of the University of Dar es Salaam to varify the various parameters and governing equations of flow, settling patterns in basin and the efficiency. The model results are in dimensionless quantities making it uncumbersome to transfer them to prototypes. The basin design is based on three main "constraints" — the use of locally available materials, minimizing financial investment and the use of local expertise, in short, optimizing the available resources.

Description of model versions

Two versions are studied to compare results obtained. The first version is the horizontal floor type with "Tangential inlet" and "normal outlet" and the second is with sloping floor (s = 10 %) other structures remain the same (as described in Mashauri 1981, Komba 1982). In both versions inflow discharges Q_i = 20 l/s, 25 l/s and 30 l/s are used while the orifice diameters are from 2 cm, 4 cm, 5 cm, 6 cm, 8 cm, 10 cm and 12 cm. The particle size ranges were $0.125 \leq D_s \leq 0.25$ mm, $0.25 \leq D_s \leq 0.4$ mm, $0.4 \leq D_s \leq 0.5$ mm, $0.5 \leq D_s \leq 1.0$ mm to $1.0 \text{ mm} \leq D_s \leq 2.00$ mm. The last two fractions were deleted from the matrix as their settling efficiences were almost 100 %.

SETTLING THEORY IN THE VORTEX-TYPE BASIN (HORISONTAL FLOOR VERSION)

Basic flow equations

The flow characteristics in a vortex basin are best described by the Navier-Stokes equation of change (Cecen and Akmandor 1973, Mashauri 1981) (Fig. 1).

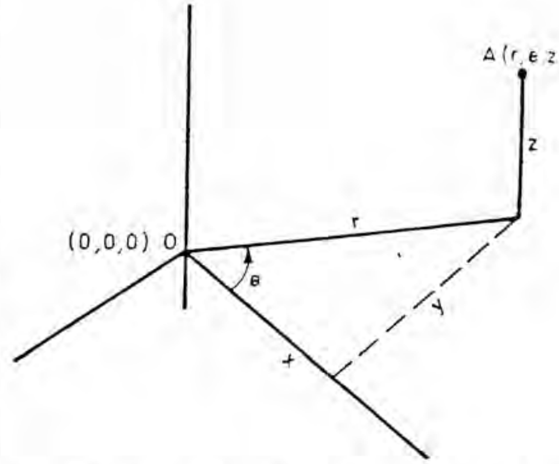

Fig. 1. Definition sketch of infinitesimal particle element with respect to "O".

Starting from the separation of the pressure tensor from the viscous tensor (without reproducing details elaborated in Cecen and Akmandor 1973, Mashauri 1981) one can obtain the following three main equations to describe, in substantial derivatives, the main velocity components in the basin. However, two main assumptions abound here — the fluid is ideal therefore the density is constant and the viscosity is zero (or $\frac{\partial \rho}{\partial t} = 0, \upsilon = 0$)

$$\frac{D}{Dt}(Ur) - \frac{U\theta^2}{r} = -\frac{1}{\rho}\frac{\partial}{\partial r}(p + \gamma h) \quad \ldots (2.1)$$

$$\frac{D}{Dt}(Uo) - \frac{U\theta Ur}{r} = -\frac{1}{\rho}\frac{\partial}{\partial r}(p + \gamma h) \quad \ldots (2.2)$$

$$\frac{D}{Dt}(Uz) = -\frac{1}{\rho}\frac{\partial}{\partial_z}(p + \gamma h) \quad \ldots\ldots\ldots (2.3)$$

Cylindrical coordinates according to Fig. 1 are applied in the above equations.

The flow in the basin can be categorized in three main classes. The peripheral flow (rotational flow zone) has its velocity components at any arbitrary point as $U_r = 0$, $U_\theta = \omega r$, $U_z = 0$) and is bounded within $R_c \leq r \leq R$ which is between the critical radius and the basin radius Fig. 2.). The pressure in z-direction in this zone is essentially static or $\frac{P}{\gamma} + h$ = constant. Also

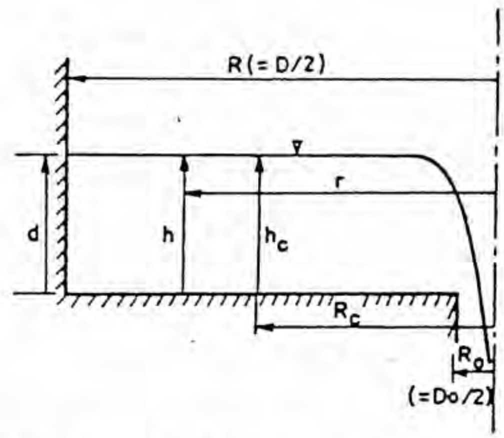

Fig. 2. Flow zones in the settling basin.

$$\frac{U_\theta^2}{2g} = \frac{\omega^2 r^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(2.4)}$$

And the water depth is given as

$$h = d - \left(\frac{\omega^2}{2g}\right)(R^2 - r^2) \quad \ldots\ldots\ldots\ldots \text{(2.5)}$$

which gives the angular velocity the form

$$\omega = \sqrt{2g\left(\frac{d-h}{R^2 - r^2}\right)} \quad \text{(2.5a)}$$

In zone II ($R_o \leqslant r \leqslant R_c$) which is characterized by potential rotational flow (Rankin flow), the velocity components are $U(U_r = 0$, $U_\theta = C/r$, $U_z = 0)$. The pressure distribution in z-derection is constant or $\frac{P}{\gamma} + h$ = constant giving

$$h = h_c + \frac{C^2}{2g}\left[\frac{1}{R_c^2} - \frac{1}{r^2}\right] \quad \ldots\ldots\ldots\ldots \text{(2.6)}$$

$$\text{or } C = \sqrt{2g\left(\frac{h_c - h}{\frac{1}{r^2} - \frac{1}{R_c^2}}\right)} \quad \ldots\ldots\ldots \text{(2.6a)}$$

where C is the vorticity force.

The turbulent zone $0 \leqslant r \leqslant R_o$ has quite other flow characteristics different from those of the former zones. It is unique in this zone III thet $U_z \neq 0$. The velocity components are

$$U_r = -\frac{Q_o}{2\pi R_o^2 h_o} r \quad \ldots\ldots\ldots\ldots\ldots \text{(2.7a)}$$

$$U_\theta = \frac{C}{r} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.7b)}$$

and

$$U_z = \frac{Q_o}{\pi R_o^2 h_o} z \quad \ldots\ldots\ldots\ldots\ldots \text{(2.7c)}$$

Discharge at any radius r from orifice center's given by the following expression

$$\frac{Q_r}{Q_o} = \frac{r^2}{R_o^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.8)}$$

Determination of main parameters

Determination of "ω" in zone I $R_c \leqslant r \leqslant R$

It is evident from equation 2.5a that "ω" is a function of the inflow discharge Q_i, basin diameter D, water depth h, orifice to basin diameter ratio $\frac{D}{D_o}$ or $\omega = \phi(Q_i, D, \frac{D}{D_o}, h)$ (Mashauri 1981).

With the help of the famous Buckingham's Π theorem one can make a thorough dimension analysis of these factors to arrive at a function of this form

$$\omega = k\frac{Q_i}{D^{5/2} h^{1/2}} \quad \ldots\ldots\ldots\ldots\ldots \text{(2.9)}$$

k is the dimensionless constant which can be determined with the model experiments as

$$k = \frac{\omega h^{1/2}}{Q_i} D^{5/2} \quad \text{as a function of } \frac{D}{D_o}$$

Determination of "C" in zone II $R_o \leqslant r \leqslant R_c$

The strength of vortex "C" is a function of the discharge Q_i basin diameter D, its ratio to orifice diameter $\frac{D}{D_o}$ and the water depth of $C = \phi_1(Q_i, D, \frac{D}{D_o}, h)$ again with the heip of the Π theorem, an expression of the form is obtained

$$C = k_1 \frac{Q_i}{(Dh)^{1/2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2.10)$$

From the model, values of k_1 (dimensionless factor) can be determined as function of D/D_o.

Determination of sediment movement, path and efficiency of the basin

The most important thing is to show the relation between flow velocities and the sedimentation in the basin. Sedimentation will to a large extent be influenced by the particle fall velocity "W". The fall velocity is howewer very much a function of the flow zone in which the particle is. In summary fall velocities are as follows (Camp 1946, Mashauri 1981) (Fig. 3.).

Zone I $R_c < r < R$ Stokes zone $R_e < 0.5$

$$\rightarrow C_D = \frac{24}{R_e}$$

From Stokes Law (Camp 1946)

$$W = \frac{g}{18} \frac{\gamma s^1}{\gamma w} \frac{D_s{}^2}{\upsilon} \quad \ldots\ldots\ldots\ldots\ldots (2.11)$$

Zone II $R_o < r < R_c$ Transition zone $R_e < 10^4$

$$C_D = \frac{24}{R_e} + \frac{3}{\sqrt{R_e}} + 0.34$$

$$W = K(g\upsilon\gamma_s^1)^{1/3}$$

$$k = \frac{W}{(g\upsilon\gamma_s^1)^{1/3}} \quad \ldots\ldots\ldots\ldots\ldots (2.12)$$

Zone III $o < r < R_o$ Turbulent zone $R_e > 10^4$

$$\rightarrow C_D = 0.4$$

$$W = \sqrt{3.3\, g \frac{\gamma_s^1}{\gamma w} D_s} \quad \ldots\ldots\ldots\ldots (2.13)$$

υ is the kinematic viscosity of the fluid
D_s is the particle diameter ($= D_{50}$)
C_D is the drag coefficient

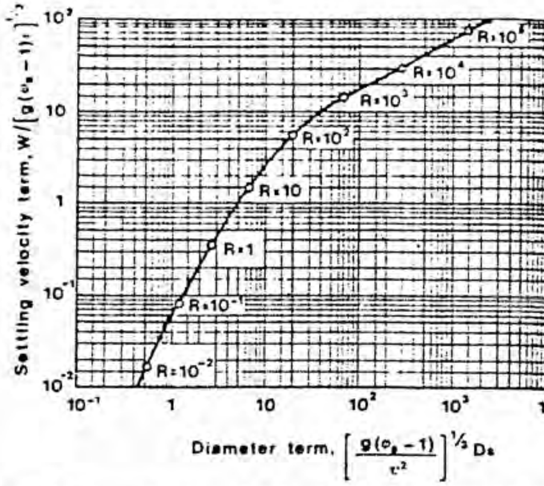

Fig. 3. Determination of fall velocity in the transition zone.

The sediment particles will also be subject to the shear stress velocity $U_\star$ at the bottom of the basin which is a function of the flow velocity U and λ which is Darcy-Weisbach frictional coefficient. (Camp 1946, 1953)

$$\frac{U}{U_\star} = \sqrt{\frac{8}{\lambda}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.14)$$

Silting efficiency η of the basin is $\eta = \frac{q_s(\text{silting})}{q_s\,(\text{in flow})}$ and is a function of the shear stress at bottom of basin τ_o, fall velocity W, water depth h, water density ρ, basin diameter D, and the flow velocity U, or

$$F(\tau_o, W, h, \rho, \frac{D}{U}, \eta) = 0$$

dimensionless quantities $\frac{W^2}{\frac{\tau_o}{\rho_w}}$ and $\frac{WD}{Uh}$ describe the basin efficiency

$$\text{correctly as } \eta = \phi \left[\frac{W^2}{\frac{\tau_o}{\rho_w}}, \frac{WD}{Uh} \right] \quad \ldots\ldots\ldots (2.15)$$

Therefore

$$\because \frac{\tau_o}{\rho_w} = U_\star^2 \quad \text{Then } \eta = \phi \left[\frac{W^2}{U_\star^2}, \frac{WD}{Uh} \right] \quad \ldots (2.15a)$$

and can be determined with model studies.

From model studies it was clear that the optimum basin diameter is given by

$$D = 5.274\,(U_\star/U)^{1/4}\,(k_1 \cdot k_2)^{1/4}\,(Q_i/W)^{1/2} \quad \ldots\ldots(2.16)$$

and basin height is given as

$$h = k_1 U_\star D/k_2 U \quad \ldots\ldots\ldots\ldots\ldots (2.17)$$

where

- D is the basin diameter
- Q_i is the inflow discharge
- $U_\star$ is the shear velocity
- U is the flow velocity
- h is the basin height
- W is the fall velocity of representative particle ($D_2 = D_{50}$)
- $k_1 = \frac{W}{U_\star}$ is the mobility number of the sediment particles
- $k_2 = WD/Uh$ is the settling coefficient of the particles and
- D_s is the mean particle diameter ($D_s = D_{50}$)

k_1 and k_2 can be obtained from Fig. 4.

RESULTS OF THE EXPERIMENTS

Horizontal floor variant

- The angular velocity was determined in the model studies as $\omega = k\frac{Q_i}{D^{5/2}h^{1/2}}$ as a function of D/D_o
- The results show that (Mashauri 1981)

$$\omega = 88.25\,\frac{Q_i}{D^{5/2}h^{1/2}} \quad \ldots\ldots\ldots\ldots (3.1)$$

- The vorticity force C has the following form

$$C = 16.33\frac{Q_i}{Dh} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

- The silting parameter $\frac{WD}{Uh}$ and the moving $\frac{W}{U_\star}$ were determined in the model studies. The shear velocity $U_\star$ differs in each zone as follows in zone I ($R_c < r < R$) equation 2.14 gives

$$U_\star \doteq 0.07U \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

With equations (3.3) and (3.4) $\frac{W}{U_\star}$ were determined in the two zones and their plots versus basin efficiency η, and moving parameter $\frac{WD}{Uh}$ are in Fig. 4.

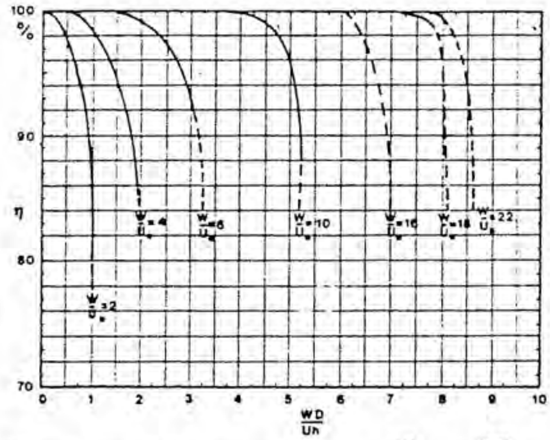

Fig. 4. Removal efficiency as function of $\frac{W}{U_\star}$ and $\frac{WD}{Uh}$.

Sloping floor variant (s = 10 %)

Figures 5 and 6 depict the results from this basin version. The particle removal efficiency is

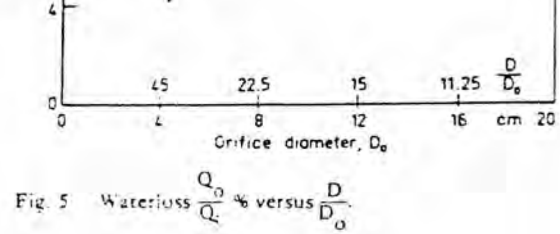

Fig. 5 Waterloss $\frac{Q_o}{Q_i}$ % versus $\frac{D}{D_o}$.

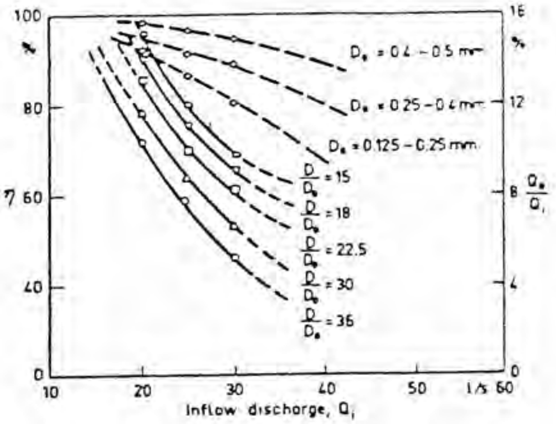

Fig. 6. Removal efficiency, η, and loss of water, $\frac{Q_o}{Q_i}$, as functions of inflow discharge Q_i. Symbols of dashed curves represent group means.

higher than that of the horizontal floor version though more water is lost through the flushing orifice (Komba 1982).

CONCLUSIONS AND RECOMMENDATIONS

- Water loss through the orifice in both versions ranged between 5–15 % of the inflow. The loss was almost proportional to the orifice diameter D_o refer to Fig. 5.
- The basin diamensions are small compared to classical basins (at comparable overflow rates) making it more economical to use vortex-type settling.
- Since the basin can remove particles > 0.2 mm efficiently their use in hydropower intakes is recommended.
- To some extent smaller particles can also be removed giving a possibility for their services in water supply intakes as primary clarifiers.
- This type of basin can also be used at the irrigation headworks to deter sediment particles from entering the irrigation canals downstream.
- Their use as "sand cleaners" at water treatment plants especially those using slow sand filters is a viable possibility.
- In potable water treatment they could be used before roughing filter and slow sand filter units.
- It is possible to use this type of basin to clarify wastes from fish hatcheries.
- More research in this direction would be profitable especially to rural water supply programmes.
- The researcher is currently carrying out laboratory scale model tests of the basin, at the Tampere University of Technology to varify further the sediment separation efficiency, the hydraulic performance and the cost of the system.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the financial support received from the University of Dar es Salaam in the form of Research Grant. He also thanks Prof. Matti Viitasaari of the Tampere University of Technology for encouragement and helpful discussions.

LIST OF SYMBOLS

A	=	arbitrary point in space
C	=	vorticity force
C_d	=	drag coefficient
D	=	diameter of basin
D_o	=	diameter of orifice
d	=	depth of water in the basin at side wall
D_s	=	particle deameter
g	=	gravitational acceleration
h	=	depth of water at any radius r
h_c	=	critical depth at $r = R_c$
k_i	=	dimensionless coefficient
o	=	original/reference point
p	=	water pressure
Q	=	volumetric flow of water per unit time
Q_i	=	inflow

Q_o = outflow through orifice
q_s = sample weight of material
R = radius of basin
R_c = critical radius at $h = h_c$
R_e = Reynolds number
R_o = radius of orifice = $\frac{D_o}{2}$
s = slope of basin floor
U = flow velocity
U_θ, U_r, U_z = respectively flow velocity components in θ, r, and z directions (cylindrical coordinates)
$U_\star$ = shear velocity
W = fall velocity of particle in water
x, y, z = rectangular coordinates
γ = specific weight of water
γ_s = specific weight of particles
υ = kinematic viscosity of fluid
Ø = function
ρ = density (ρ_w for water, ρ_s for particles)
τ_o = shear stress
η = settling efficiency
ω = angular velocity
λ = Darcy–Weisbach friction coeffient

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Received November 1983