Tubular storage tanks with internal throttle pipe for usage in densely urbanized areas

Stockage souterrain des eaux pluviales dans des conduites circulaires avec un réducteur de débit, pour une utilisation en sites urbains denses

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RESUME

Cet article décrit la construction de bassins de rétention avec une tubulure interne d’étranglement conçue pour la gestion des eaux pluviales dans une zone urbaine dense. Ils peuvent être utilisés dans des systèmes d’égout séparatifs existants ou nouveaux (dans les systèmes unitaires avec certaines réserves), pour augmenter la capacité de stockage à un faible coût d’investissement. La recherche de vérification à l’échelle de laboratoire (pour un diamètre de conduite de stockage de 290mm) a confirmé la précision du modèle mathématique des bassins. Des simulations hydrodynamiques ont été effectuées en SWMM5 pour deux évènements de pluviométrie et un diamètre de conduite de stockage de 2m montre un rendement notablement plus élevé des constructions proposées par rapport à un bassin à chambre unique avec un orifice comme régulateur de flux.

ABSTRACT

The papers presents a construction of a detention tanks with internal throttle pipe designed for stormwater management in densely urbanized areas. They can be used both in existing and new separate sewer systems (in combined systems with some restrictions) to increase the storage capacity at low investment cost. Verification research at laboratory-scale (for storage pipe diameter 0,29m) have confirmed an accuracy of a mathematical model of the tanks. Hydrodynamic simulations have been made in SWMM5 for two rainfall events and storage pipe diameter equal to 2.0 meters shows significantly higher efficiency of the proposed constructions in comparison to a single-chamber tank with orifice as flow regulator.

KEYWORDS:

Detention facilities, drainage systems, stormwater.

1 INTRODUCTION

Detention facilities are commonly used to manage the quantity of stormwater on existing urbanized as well as newly developed areas. They are intended to control peak flows, limit downstream flooding, and provide some channel protection (Degroot, 1983). In areas where the drainage infrastructure already exists, retrofitting these systems to provide flow control can be prohibitively expensive (Saul and Ellis, 1990). In these cases, the in-line detention tanks can be alternatively applied, specially on densely built-up areas where the available space for on-site detention facilities is highly limited. The in-line tubular tanks are constructed in series with the sewer network and are controlled by a flow control device at their outlet . The detention reservoirs made of large diameter pipes (1,5÷3,0m) have been constructed tens years ago in many countries. Usually such constructions are realized as single-chamber with the orifice as the flow regulator (Butler and Davies, 2000). The single-chamber reservoirs have a number of disadvantages, the main are (Becker et. al,2001; Mrowiec and Kisiel, 2005b) :

- maximum outflow rate is achieved only when the tank is full of stormwater,
- main detention chamber is polluted frequently (in combined sewer systems - continouosly) causing a sediment disposal problems.

The detention facilities with side weir are characterized by a better hydraulic performance because the detention chamber is filling when the outflow is equal near to maximum release flow rate.
A new conception of tubular detention tanks is based on two main assumptions:

- tank operates as in-line device (recommended for densely built-up areas where the available space on-site is limited),
- the hydraulic performance is equivalent to the reservoirs with a side weir.

Additional assumptions made for the constructions: low investment and maintenance costs, no external power required, minimize the number of mechanical parts and reliability issues have been taken into consideration.

2 PROPOSED CONSTRUCTIONS OF THE TUBULAR STORAGE TANKS WITH INTERNAL THROTTLE PIPE

2.1 The constructions overview

Based on abovementioned assumptions the improved constructions of tubular storage tanks have been proposed:

- reservoir with throttle pipe and float valve as the flow regulator (RPF) see fig.1a.
- reservoir with throttle pipe and orifice as the flow regulator (RPO),
- inversely sloped reservoir with throttle pipe and flap valve (RTI) see fig. 1b.

All the construction have three chambers: an inlet, an outlet and storage but they are different in details. The construction of the RPF and RPO tanks is quite similar - an inlet and outlet chamber are connected by the throttle pipe, , lying on the bottom of the main chamber. The partition wall, separating the inlet and main detention chamber is also a weir of given crest elevation. The main difference between the RPO and RPF tank is the outflow regulation from the main storage chamber. RPF tank has the float valve regulator which holds stormwater during inflow phase while for RPO tank the flow regulation is performed by the properly designed orifice (optionally the Vortex regulator may be installed). The difference causes less hydraulic efficiency for RPO tank, but it’s more reliable solution due to lack of mechanical parts.

The RTI construction is specific because the main storage pipe is inversely sloped as well as the throttle pipe inside. It allows to limit the cover depth of the outlet channel but significantly changes the function of the inlet chamber - it can be arranged as grit chamber or as an infiltration one. The infiltration purpose is suitable only when the groundwater conditions are favourable (filtration coefficient $>10^{-5}$ m/s) and the stormwater contamination will not produce the accelerate colmatation. Otherwise the grit chamber is only option but then the RTI tank has a permanent pool of stormwater. This volume is usually less than $10m^3$ - insignificant in comparison to total available volume.

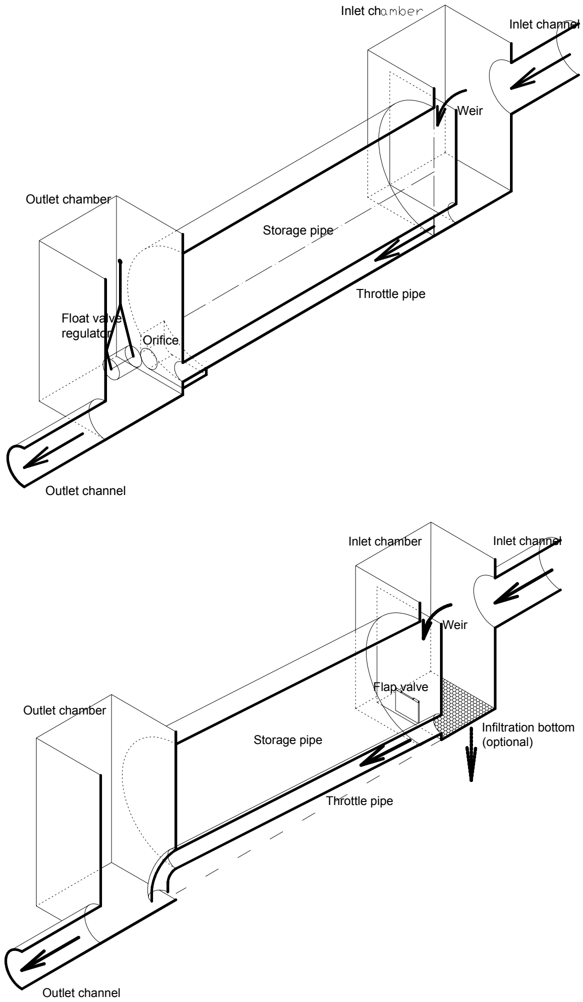

Fig. 1. Izometric view of the detention tanks: a) RPF, b) RTI. The RPO tank has the same construction as RPF except the float valve.

Both RPO and RPF tank can be applied to combined and separate sewer systems, while the RTI tank can be applied to separate ones only.

2.2 Theoretical model of the proposed tanks

Three main phases can be distinguished during typical wet weather conditions :

- flow-through phase (inflow Q_M is smaller than outflow Q_0),
- storage phase (inflow Q_M is greater than outflow Q_0 and the difference (Q_R) is discharged to detention chamber),
- emptying phase (inflow Q_M drops below Q_0 and main chamber is released).

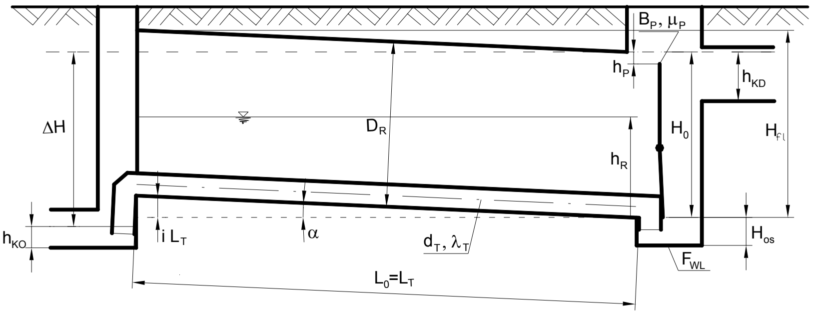

Fig 2. The scheme of RTI tank for mathematical model.

The flow-through phase is similar for all the tanks - during low flows, stormwater partially filling the inlet chamber and flows via the throttle pipe to outlet chamber. Due to its small volume, the inlet chamber is filled in relatively short time, while the main detention chamber remains empty.

During intensive rainfall the inflow-rate increase cause the water overflow through the weir to the main storage chamber. During detention phase outflow through the orifice is restricted due to action of the float valve in the RPF tank. Water at outlet chamber lifts the float and simultaneously covers the orifice. In the RTI tank outflow from storage chamber is also limited by the flap valve located at inlet chamber.

A mass conservation law is based on the model equations that describe the process of sewage storage in a reservoir (Gribbin, 2001; Durrans 2002). For the inlet chamber during storage phase (Q_M>Q_0) the differential equation has the following form:

$$\frac{dh_0}{dt} = \frac{Q_M dt - Q_T dt - Q_R dt}{F_{(h_0)}}$$

where: Q_M – inflow rate [m^3/s],
Q_T – outflow rate through the throttle pipe [m^3/s],
Q_R – outflow rate to the storage chamber [m^3/s],
h_0 – depth at the inlet chamber [m],
$F_{(h0)}$ – area of free surface of water at the inlet chamber [m^2].

simultaneously for the storage chamber:

$$\frac{dh_R}{dt} = \frac{Q_R}{F_{(h_R)}}$$

where: h_R – depth at the storage chamber [m],
$F_{(hR)}$ – area of free surface of water at the storage chamber [m^2].

To calculate the overflow discharge Q_R, the standard relationship between the flow-rate and depth for the rectangular weirs can be used with assumption that weir is: sharp crested, non submerged and no contracted. Transitional flow-rate Q_T can be described on the basis of Bernoulli equation, comparing the total energy at the inlet and the outlet chambers.

For the RPO tank the storage phase have a different course - the outflow rate Q_0 is a sum of flow through throttle pipe Q_T and orifice Q_Z, so the balance equation for storage chamber have a form (Mrowiec and Kisiel, 2005a):

$$\frac{dh_R}{dt} = \frac{Q_R - Q_Z}{F_{(h_R)}}$$

where: Q_Z – flow-rate through the orifice.

Therefore the total outflow rate from the tank is a sum of Q_Z and Q_T and relationship between them also determine the required storage capacity of the reservoir.

When inflow-rate is less than outflow-rate ($Q_M<Q_0$), the inlet chamber is evacuating quickly (RPF and RPO tanks) due to its small volume. In the RPF tank the float valve gradually opens the orifice allowing to release retained stormwater while in the RPO tank the orifice have no mechanical regulator. The flow-balance equation for storage chamber:

$$\frac{dh_R}{dt} = \frac{-Q_Z}{F_{(h_R)}}$$

To calculate discharge through the orifice a standard equation for such devices can be applied. In the RTI tank the stored stormwater is released through the flap gate at inlet chamber controlled by the hydrostatic forces (as difference between depths at inlet and storage chamber). Then, via the throttle pipe, flows to the outlet channel.

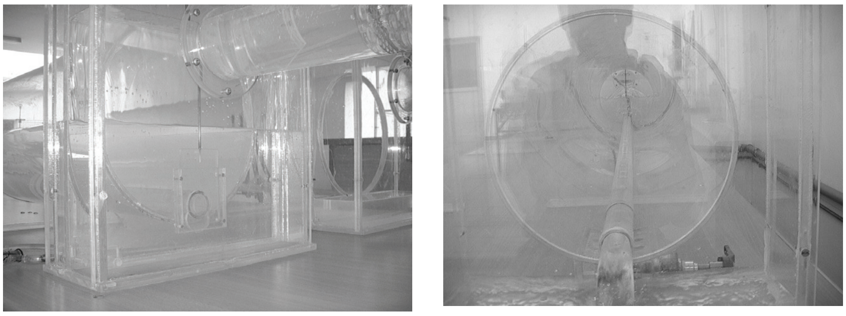

Fig. 3. Model of the RPO tank during verification research: a) inlet chamber b) outlet chamber - the main detention chamber with throttle pipe is visible.

The formulated mathematical models have been verified in laboratory conditions by means of physical models. Main dimensions of the models: length L=2,10 m, storage diameter D_R=0,29 m (total volume of 0.14 m^3), throttle pipe diameter d_T=0,03m The research was conducted for the inflow-rate ranged from 0,2 to 2,0 dm^3/s taking into consideration different values of flow reduction factor β (defined as the ratio of maximum outflow to maximum inflow-rate). The flows relative error ranged from 1% to 12% but the highest values occur during release phase, when the depths were smaller than throttle pipe diameter (d_T). Generally the models allow to estimate main parameters with fairly good precision, enough to engineering purposes.

3 HYDRODYNAMIC MODEL OF THE PROPOSED TANKS

In order to evaluate the hydraulic efficiency of the proposed constructions in the particular drainage systems, the single event simulation have been done using SWMM5 application. Densely built-up watershed of the Czestochowa city, routing stormwater to Warta river, was chosen to compare the hydraulic properties of the in-line reservoirs made of large diameter pipes. The simulation have been done for two rainfall events (both hydrographs have been simplified to linear functions):

- 1-hour rainfall, treated as critical rainfall,
- 4-hour rainfall with two peak flows.

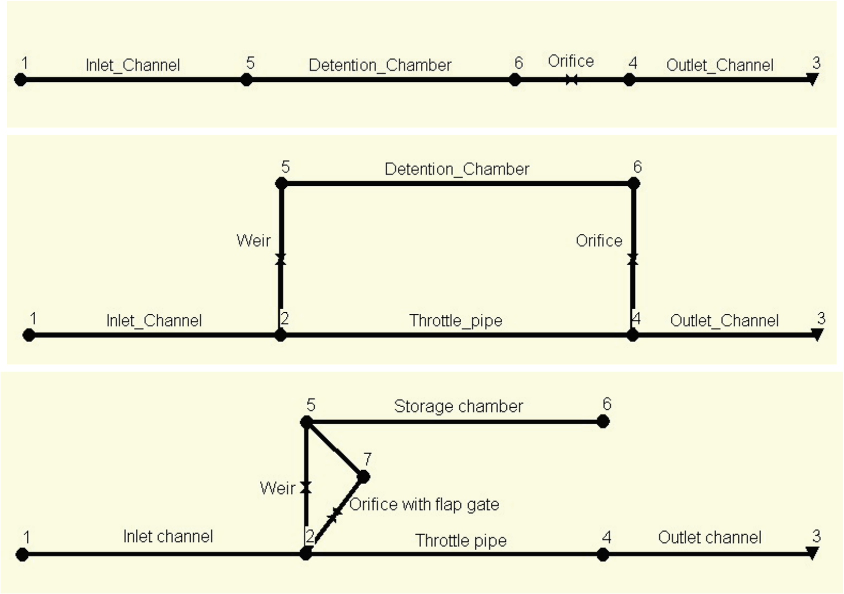

Fig. 4. Scheme of proposed detention tanks used in SWMM5: a) single chamber b) RPO (RPF has additional control rules for the orifice), c) RTI.

Figure 4 presents schemes of the tubular tanks to run a hydrodynamic simulation in SWMM (dynamic wave routing: 1sec). Primary model assumptions were:

- 1-hour rainfall is a critical for the single chamber tank (the tank is completely filled),
- maximum outflow rate from the tanks: 0,145 m^3/s
- storage chamber diameter: 2,0m; length: 150m; slope: 0,5% (except the RTI tank which is inversely sloped and the outlet channel elevation was 0,55m higher),
- the throttle and orifice diameters were different for each reservoir to meet the outflow requirements,
- for the RTO tank the flow-ratio Q_T/Q_0=0,67.

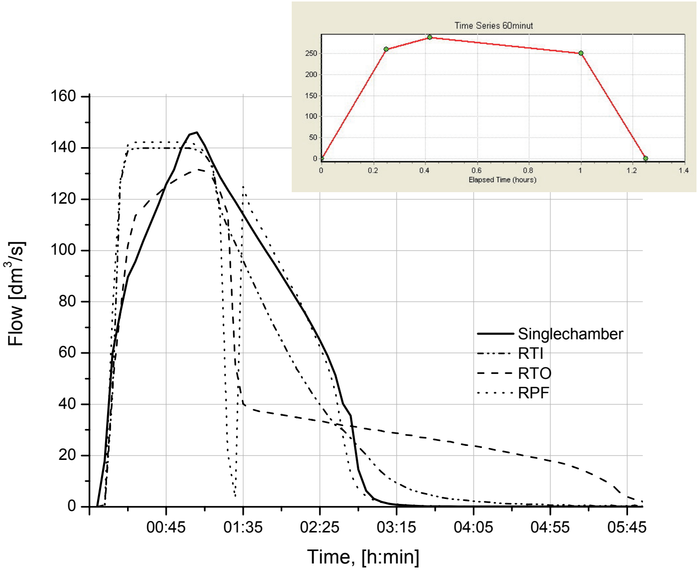

Fig. 5. Outflow hydrographs from the different types of the tanks (hydrograph of the 1-hour rainfall above the curves).

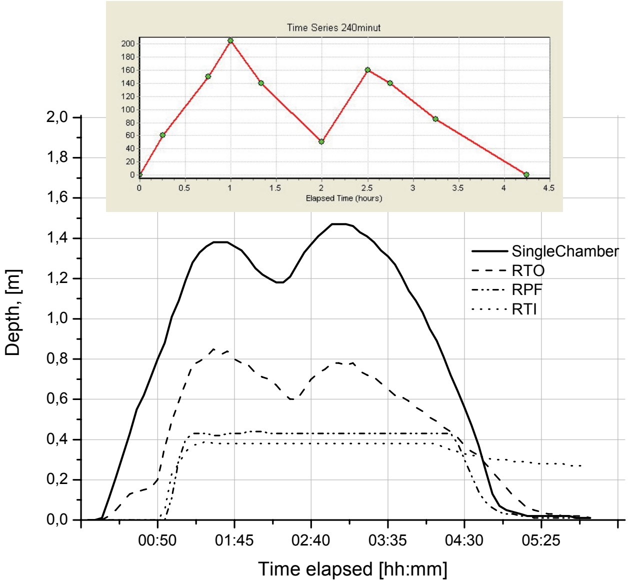

Fig. 6. Depth at storage chamber for particular type of tank (hydrograph of the 4-hours rainfall above the curves).

Simulation results for critical (design) storm confirmed the results obtained for hydrographs tested at laboratory-scale. The single-chamber tank geometry was shaped to be completely filled. The efficiency of RPF and RPO tanks was significantly higher than for single chamber ones – the volume required can be reduced by as much as 34% (RTI tank) and 37% (RPF tank). For the RPO tank the possible volume reduction is about 18% because it is some kind of compilation between the single-chamber and the RPF tank.

The second rainfall event characterized by significantly lower peak flows but 4-times longer duration cause the following maximum filling-rate for each tank: single-chamber: 63%, RPO: 31%, RPF and RTI: 10% (excepting the permanent pool in the RTI tank). Such results shows the potential efficiency of proposed constructions during the long-term simulations should be greater than for single critical storm. For many low-intensity rainfall events the multi-chamber constructions allow to avoid the stormwater discharge to storage chamber. Therefore a problem of sewage solids deposition can be reduced to minimum as well as the maintenance costs.

4 CONCLUSIONS

Proposed constructions of the in-line detention tank with throttle pipe located inside the storage chamber make possible to better utilization of storage capacity in comparison to single-chamber tanks for equivalent performance. Theoretical flow route model has been developed for each type of the tank and successfully verified at laboratory-scale. Hydrodynamic simulations in SWMM5 have been made for the innovative tanks on sample catchment show the potential volume reduction from 18 to even 37% in comparison to single-chamber tubular reservoir. All the presented constructions may be applied in existing and new sewer systems at relatively low capital costs and assure lower maintenance costs due to lower cleanse needs.

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