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DESIGN RECOMMENDATIONS FOR WASTEWATER PUMPING STATIONS – RESULTS FROM MODEL TESTS

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ABSTRACT

Pumping stations are essential components in wastewater systems. At these nodes, wastewater from the sewer network is collected and conveyed, for example to the downstream wastewater treatment plant. Due to this key position in the wastewater system, the trouble-free operation of these pumping stations is of utmost importance.

Since wastewater is generally a very inhomogeneous media, which carries a variety of solids (sand, gravel, wet wipes, etc.), these interfering substances result in a variety of negative effects on the operation of wastewater systems. The main challenges in designing pumping stations result from: air entrance, sedimentation, swimming layers and clogging of pumps.

The presented paper deals with recommendations for designing pumping stations regarding sedimentation based on investigations in downscaled models and their transfer to original systems. The studies focus on geometrical design criteria: the overall shape of the pit, the inlet, the sloped walls, the sump, etc.

physical model, pumping station, sedimentation, sump, wastewater,

NOMENCLATURE

A	$[m^2]$	area
D	$[m]$	characteristic length (e.g. diameter)
F	$[kgm/s^2]$	force
Fr	[-]	Froude Number
g	$[m/s^2]$	gravitational acceleration
L	$[m]$	Lenght
M	[-]	Scale
Q	$[m^3/s]$	flow rate
Re	[-]	Reynolds number
T	$[s]$	time
v	$[m/s]$	velocity
We	[-]	Weber number
ν	$[m^2/s]$	kinematic viscosity
ρ	$[kg/m^3]$	density
σ	$[N/m]$	surface tension

Subscripts and Superscripts

O	original
M	model

1. INTRODUCTION

Industrial and municipal wastewater is collected in the sewage system and conveyed further to the treatment plants. Pumping stations are an integral part of these complex systems.

To prevent wastewater overflow and the associated environmental pollution, disruptions must be prevented along the entire transport chain.

A variety of challenges such as sedimentation, air entrainment [1] and swimming layers [2] may occur in wastewater pumping stations. These compromise the safe and reliable operation and thus result in increased maintenance costs. The susceptibility to these issues may be influenced by a suitable design of the entire pumping station (shape of the pit, inlet, wall geometry, etc.) as well as the choice of the used pumps.

1.1. Wastewater Pumping Stations

Wastewater pumping stations differ in size and design. The location and the type of machines influence the design parameters of pumping stations. For example, the requirements for pumping stations in rural areas differ from those in urban areas in terms of the composition of wastewater and its capacity. Two types of machines are commonly used in pumping stations: dry-installed pumps are housed in an additional machine room as shown in Fig. 1a), whereas wet-installed pumps are embedded in the suction chamber as shown in Fig.1b) and are surrounded by wastewater. Dry-installed designs may result in higher construction costs, however, the pumps are easier to access when required [3].

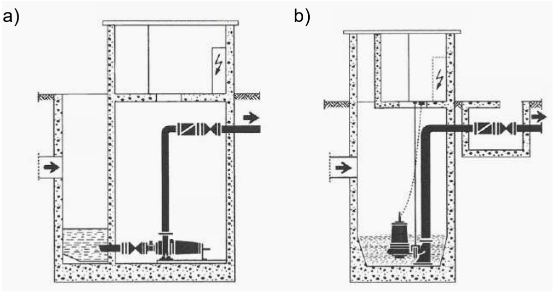

Figure 1. Sectional view of a suction chamber with a) dry-installed, b) wet-installed pumps after [3]

Even though wastewater pumps are essential components in the design and operation of wastewater pumping stations, the following investigations focus on structural investigations, especially the suction chambers of the pumping stations. The interaction between pump and wastewater is restricted to pump positions and volumetric flows. For a more detailed interaction, reference can be made to the following studies [1, 4]

This paper aims to present research approaches for designing wet pit pumping stations regarding sedimentation based on investigations in downscaled models and their transfer to original systems. The studies focus on geometrical design criteria: the overall shape of the pit, the inlet, the sloped walls and flushing routines.

More detailed studies on the problem of air entrainment were presented in [1].

1.2. Physical Model Studies

Detailed, preliminary investigations are necessary for the design of complex hydrodynamic systems to guarantee the desired functionality in the subsequent operation. A physical model investigation is a tool for analysing the correlations of design parameters. This tool enables the validation of cost-intensive issues in advance and verification of potential modifications. In the field of wastewater pumping systems, model investigations are useful for non-standard designs. These can be prototypes for novel designs or modifications for existing structures due to changed operation conditions.

2. METHOD

2.1. Dimensioning

To be able to carry out meaningful model investigations of scaled, hydraulic structures, compliance with relevant similarity laws is of utmost importance.

The geometric similarity between the model and the original must be maintained, which means that dimensions between the two investigated systems must be in a defined relationship to each other [5].

$$M = \frac{L_M}{L_O} = const. \qquad (1)$$

Furthermore, the dynamic similarity must be ensured, which brings forces acting on the respective fluid of the model and the original into a defined relationship. For the design of hydraulic models with open surfaces, the Froude number Fr, which is a ratio of inertial force to gravitational force, can be used [5, 6].

$$Fr = \frac{v}{\sqrt{g \cdot D}} \qquad (2)$$

To ensure Froude similarity between the model and the original, the respective Froude numbers must be identical [5, 6].

$$\frac{Fr_M}{Fr_G} = 1 \qquad (3)$$

When designing the model, further attention must be paid to selecting a design range in which viscous and surface tension effects are negligible. These effects can be estimated using the Reynolds number Re and Weber number We. The Reynolds number takes inertial and frictional forces into account [7].

$$Re = \frac{v \cdot D}{\nu} \qquad (4)$$

The Weber number accounts for inertial forces and surface tension forces.

$$We = \frac{v^2 \cdot D \cdot \rho}{\sigma} \qquad (5)$$

According to [7, 8], the Reynolds number is recommended to be at least above Re > 3 x 10^4. The Weber number We should be higher than We > 120. For both values, an additional safety factor of 2 is advised.

By maintaining dynamic similarity in two geometrically similar systems, the kinematic similarity is also achieved, which puts velocities and accelerations in the two systems in proportion.

If the Froude similarity adheres, various scaling rules can be applied when scaling the geometry linearly, which are listed in Table 1.

Table 1. Froude similarity scaling rules [6]

Parameter	Conversion
Lengths	$L_O/L_M = M$
Areas	$A_O/A_M = M^2$
Velocities	$v_O/v_M = M^{1/2}$
Times	$T_O/T_M = M^{1/2}$
Flow rates	$Q_O/Q_M = M^{5/2}$
Forces	$F_O/F_M = M^3$

2.2. Sediments

Wastewater is very diverse in its composition. In mixed sewer systems, not only water but suspended particles as well as dissolved components can be found [9]. For investigations in sedimentation of wastewater in suction chambers, it is necessary to reflect a spectrum of sedimentable particles in the wastewater.

Depending on the type and size of the particles expected to be introduced in the original, appropriate plastic particles with selected characteristics are used. For the investigation described in this paper, the following particles were selected.

Table 2. Overview of Particle Properties

Colour	Density
red	1090 kg/m^3
black	1690 kg/m^3

The red particles were chosen to represent light, fine particles. They are only slightly heavier than water and are easily activated by the flow. The black particles represent much heavier particles such as sand or stone. Fig. 2 shows the exemplary distribution of the particles used.

Figure 2. Exemplary particle distribution around a suction pipe inlet

In comparisons of actual conditions in the original structures and modelled conditions, deposits of sedimentation could be reproduced very well with the help of synthetic particles.

2.3. model tests on large pumping stations

The models test rigs were developed as a representation of existing suction chambers, which included both dry-installed and wet-installed pumps. Furthermore, systems with basins in rectangular, round and oval shapes were simulated. After reproducing the flow conditions, optimization approaches were formulated and implemented.

A rectangular model that is shown in Fig. 3 was selected to show exemplary results and recommendations for this case.

Figure 3. Test rig with the rectangular suction chamber

For the evaluation of the individual tests, schematic diagrams were created, which show the test setup and document the sediment deposits according to their colour marking as shown in Fig. 4. Pumps 1 to 6 are labelled as P1 to P6. Similarly, inlets 1 and 2 are marked as I1 and I2 and the flush pipe as F1.

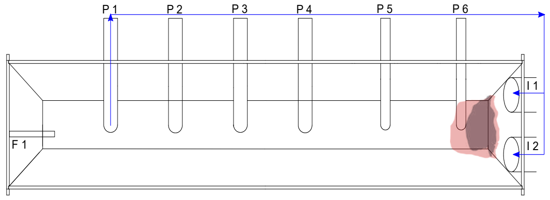

Figure 4. Schematic illustrated model test rig

All parts of the chamber and the suction pipes are made from transparent PMMA parts. This setup allows sedimentation to be viewed throughout the entire suction chamber. Table 3 gives an overview of the main model dimensions. The test rig was built as a closed system, so outgoing flow is equal to the incoming flow.

Table 3. Model Dimension

Parameter	Value
Scale	1:6.3
Length	3.8 *m*
Width	0.8 *m*
Volume	3.5 m^3
Number of Pumps	4 to 6
flow rate (model)	3.7-14.7 m^3/h
flow rate (original)	360-1440 m^3/h

3. RESULTS

3.1. angle of sloped walls

Wastewater contains various solids of different densities. To avoid deposits on the walls and to transport the solids to the suction pipes or pump inlets, the walls of the sump are designed at a defined angle. The sloping angles of 45° to 60° recommended in the literature [7] were proven in preliminary studies by the Chair of Fluid System Dynamics. In these, the sloping angle was determined for various solids that may be present in the wastewater. The investigated solids (stones, plastic, gauze bandage, paper tissue, gravel and sand) were positioned on a coated plate, which was angled until the component slid. Fig. 5 shows the sloping angles for different solids combined with various coatings. It could be shown, that an angle of 45 ° is usually sufficient to realize a sliding of sediments. However, the influence of the flow was not taken into account here.

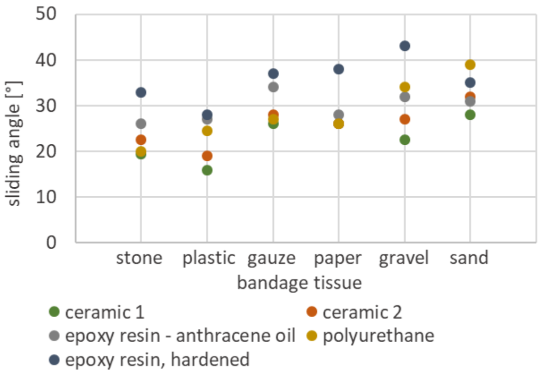

Figure 5. Test results for minimum sloping angles

Investigations of modelled suction chambers have often shown a shortfall of the recommended minimum angle. Increased sedimentation deposits occurred on these walls as shown in Fig. 6. Sedimentation on walls is significantly reduced by using angles of 45° to 60°.

Figure 6. Sedimentation deposits on sloped walls

3.2. design on basin bottom

The ability of suction pipes or wet-installed pumps to remove deposited sediments within a radius is limited. As an optimisation approach, intake manifolds can be installed to increase the operating radius. Furthermore, special attention must be paid to the surrounding sloped wall geometry and other built-in structures in the suction chamber. Requirements to avoid sedimentation are among other things the reduction of bottom surfaces, providing sloped walls with an angle of at least 45° as mentioned in 3.1. or an increase of the local velocity to transport particles to the operation areas of the suction pipes.

One significant obstacle of the presented model test is the marginal average velocity in the suction chamber combined with slope angles less than 45° and extended bottom surfaces. As a result, a high amount of sedimentation accumulates immediately under the inlets I1 and I2 as shown in Fig. 7. In the shown case pump number 6 was running and directly connected to the inlet. Incoming particles accumulated outside the operating radius of the suction pipe and could not be removed.

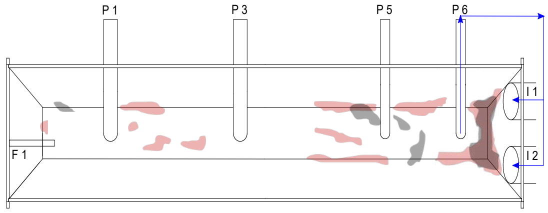

Figure 7. Particle distribution with initial suction chamber setup

Fig. 8 shows how to handle this amount of sedimentation with several combined modifications to the suction pipe design and built-in structures. In this context, the increase of the sloping wall angles up to 60° reduced the surfaces with low angles to minimize the areas of sedimentation. On the other hand, the decrease in bottom clearance increases the local velocity to move sedimentations. Filling up the edges with curved structures reduced the areas of sedimentation once again. Finally, the use of a weir prevents the particles from being scattered in the suction chamber and ensures that the deposits are collected under the suction pipe of pump 6.

The effect of this combined modification is a significantly reduced amount of sedimentation under the inlets with a focus directly under the suction pipe of a sewer pump.

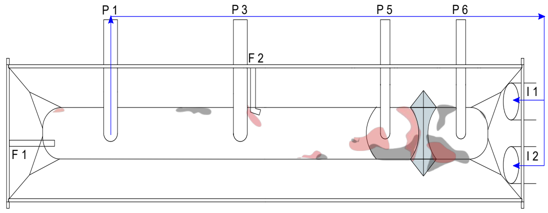

Figure 8. Suction chamber with combined design approaches

3.3. inlets direction and position

The direction and position of the inlet strongly influence the location of sedimentation areas on the bottom of the pit. In rectangular sumps, the inflow is usually carried out on the short side orthogonal to the wall. The height of the inlet combined with the water level strongly influences the movement of the sediments. While at high levels the particles deposit mostly near the inlet (Fig. 7), at lower levels a greater circulation of the flow at the bottom exists and thus a better distribution of solids is observed.

Fig. 9 shows the water level dependency that was observed in the tests. In both tests, pump 1 is used with a flow rate of 14.7 m^3/h. In Fig. 9a, the water level is 0.96 m, more than 0.5 m above the inlets. In Fig. 9b, the water level is at a height of 0.1 m, just below the inlets.

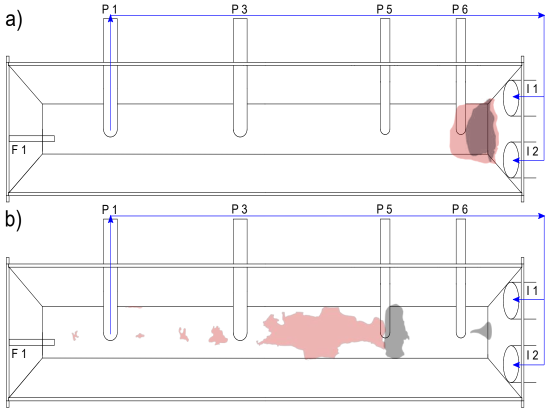

Figure 9. Particle distribution depending on a) high b) low water level

A round or oval-shaped pit offers further possibilities for the inlet design, for example, a tangential inlet offers advantages regarding sedimentation as well as reduced air entrainment and swimming layers [1, 10]. With a suitably designed wall geometry, sediments are guided reliably into the center of the pit and thus to pump sumps due to the pressure distribution in curved structures. (Fig. 10).

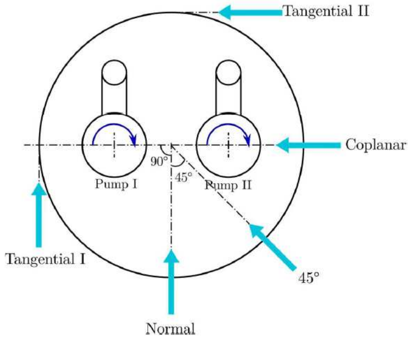

Figure 10. Variations in inlet designs in round wet pits [1]

When designing the inlet necessary minimum levels must be considered regarding air intake. This depends on the machines used as well as the inlet volume flow and the distance between the inlet pipe and the water level.

3.4. Flushing

As part of the design process, some compromises may have to be made due to the constraints of the structure. The reasons can be diverse. If sedimentation areas are not preventable the implementation of flushing can be suitable to remove accumulated sedimentations.

A flushing sequence can include some of the steps:

- stop normal operation,
- close valves to stop the incoming flow,
- adjust sewage level to a low value,

- operate a flushing pipe for a certain time,
- reduce the water level to the absolute minimum,
- open valves for incoming flow and
- start normal operation.

Flushing pipes are installed in the suction chamber and operate with one of the sewage pumps. The open diameter of the flushing pipe should provide a free jet with high velocity. Influencing test factors for flushing sequences were the position of the flushing pipe, velocity and angle of the water jet, duration of the flushing operation and water level in the suction chamber, whereas the position of the flushing pipe is especially important.

In this model test velocities up to 6 m/s were successfully investigated. Also, the combination of several flushing pipes in one suction chamber to increase the flushing effect was examined.

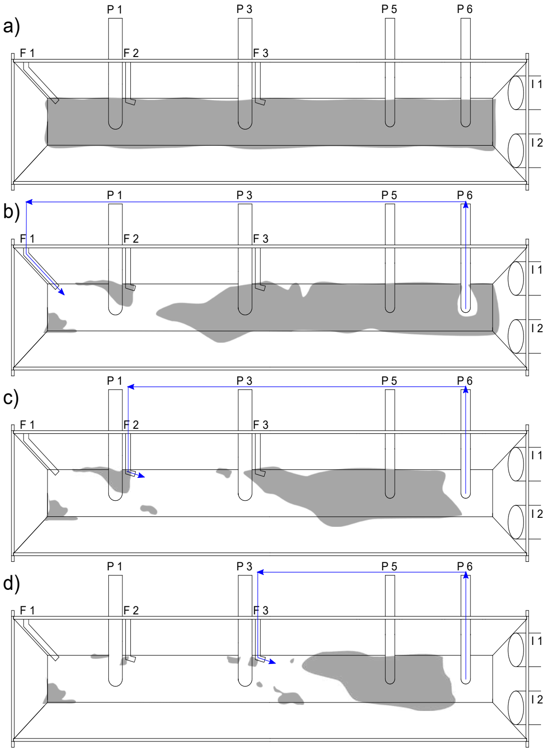

Figure 11. Removing sedimentation of the suction chamber with a flushing sequence

In the model test, shown in figure Fig. 11, a worst-case scenario was examined. The entire suction chamber bottom was covered with particles of high density. During the flush sequence flushing pipes 1 to 3 operate in sequence one at a time as illustrated in Fig. 11a)-d). Each pipe was running for 4 minutes. The result of the flush sequence was accumulated sedimentation around the low-level wastewater pumps. The flush pipes 2 and 3 increase the scope of the flushing jet and reduce the wake space between suction pipes.

5. SUMMARY

With the help of model tests, investigations can be carried out on suction chambers with dry-installed as well as wet-installed pumps. These investigations are particularly suitable for existing structures with challenging framework conditions. With this method, design investigations can be carried out on the following design parameters, among others:

- inlets
- sloped walls
- built-in structures
- suction nozzles
- flushing sequences
- air entrainment

Overall, model tests improve the operation of the suction chamber and pump stations significantly and result in a much better operation.

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