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MODEL INVESTIGATIONS OF STORM OVERFLOW WITH DISCHARGE ADJUSTMENT

The investigations covered a storm overflow model with adjustable discharge to the sewage treatment plant. When the similarity theory and dimensional analysis were used, it was possible to derive some physical formulae describing the efficiency of the overfall edge. The geometrical scale of the model was 1:15. Examples of the results obtained for single- and double-edge overfalls were discussed and referred to natural scale conditions.

DENOTATIONS

d – diameter of discharge adjusting pipe, m,
g – acceleration of gravity, m/s^2,
h_i – hydraulic head in point i, m,
h_e – hydraulic head at the end of the overfall edge, m,
i – sloping of inlet channel bottom,
l – length of overfall edge, m,
l_d – length of discharge adjusting pipe, m,
n – coefficient in Manning formula,
p – position of baffle above the bottom of the inlet channel, m,
Q – discharge, m^3/s,
Q_d – flow rate in inlet channel, m^3/s,
Q_0 – discharge from adjusting pipe, m^3/s,
R_h – hydraulic coefficient in Manning formula,
v – flow velocity in discharge adjusting pipe, m/s
α_0 – Boussinesq coefficient,
ζ – local loss factor in discharge adjusting pipe,
λ – linear loss factor in discharge adjusting pipe,
μ – discharge coefficient,
ΔH – head loss during flow in discharge adjusting pipe, m,
ξ_l – geometrical scale (length); $\xi_l = l_N/l_M$,
ξ_v – velocity scale; $\xi_v = v_N/v_M$,
ξ_Q – discharge scale; $\xi_Q = Q_N/Q_M$.

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SUBSCRIPTS

M – model,
N – nature.

1. INTRODUCTION

The function of storm water overflow is to reduce the flow rate in the sewer system during heavy rains. In a storm water overflow, discharge is adjusted by passing some portion of the strongly polluted sewage stream through the outlet pipe of appropriately fixed diameter and length, before it is sent to the sewage treatment plant. The remaining sewage portion which passes over the overfall edge is sent to the watercourse or storage tank after its passage through the stilling pond.

No mathematical formulae are available for the hydraulic dimensioning of such overflow systems. It is recommended to use the well-known expressions proposed by POLENI, ENGELS, SCHAFFERNAK or FORCHHEIMER [2], [5] for describing the efficiency of frontal or lateral overfall with no discharge adjusting pipe. As there exist substantial differences in the hydraulic conditions between systems with and without discharge adjustment, the calculating procedures, which are in use now, may lead to serious errors. It seemed, therefore, advisable to attempt a different approach to the problem.

Before starting investigations on storm overflow models, it is necessary not only to determine the similarity of natural-scale and model-scale phenomena but also to adopt appropriate methods of fitting the model-scale measured data to the natural scale. To achieve these, it is conventional to make use of physical analysis, dimensional analysis, and the theory of mechanical similarity.

2. PHYSICAL AND DIMENSIONAL ANALYSIS

Each physical equation describing some phenomenon can be assigned a dimensional equation involving a system of base quantities. When dynamic phenomena are to be described (such as the behaviour of the storm water overflow), the base quantities are length L, mass M and time T. Hence, the physical equation of the overflow (fig. 1) may be written as [2], [4], [5]

$$F(\varrho, g, h, l, p, Q) = 0 \tag{1}$$

where ϱ is water density $[\mathrm{ML^{-3}}]$, g denotes acceleration of gravity $[\mathrm{LT^{-2}}]$, h indicates height of the water layer above the overflow edge [L], l – length of the overflow edge [L], p represents elevation of the overflow edge above the channel bottom [L], and Q is the efficiency of the overflow $[\mathrm{L^3T^{-1}}]$.

By virtue of the π-theorem, the dimensions of the physical quantities included in eq. (1) may be arranged so as to give the following set of equations:

$$\pi_1 = \varrho^{x_1} g^{y_1} h^{z_1} Q,$$
$$\pi_2 = \varrho^{x_2} g^{y_2} h^{z_2} l, \tag{2}$$
$$\pi_3 = \varrho^{x_3} g^{y_3} h^{z_3} p.$$

Having the solution to this set of equations, we can find the numerical values of the exponents x_i, y_i and z_i, and determine the dimensionless products π_i. Consequently, we can derive the relation required for the qualitative description of the phenomenon. Thus, we have

$$\pi_1 = f(\pi_2, \pi_3). \tag{3}$$

The similarity of the products π_i in nature and in the model may be adopted as the similarity criterion for the investigated phenomena.

Solving the set of equations (2), we obtain

$$\pi_1 = \frac{Q}{g^{0.5} h^{2.5}}; \quad \pi_2 = \frac{l}{h}, \quad \text{and } \pi_3 = \frac{p}{h}.$$

Hence

$$\frac{Q}{g^{0.5} h^{2.5}} = f(l/h, p/h), \tag{4}$$

or

$$\frac{Q}{g^{0.5} h^{2.5}} = a\left(\frac{l}{h}\right)^{b_1}\left(\frac{p}{h}\right)^{b_2}. \tag{5}$$

It is convenient to use eq. (4) when qualifying the phenomenon of interest. Quantitative assessment requires consideration of (5) and experimental determination of a, b_1 and b_2.

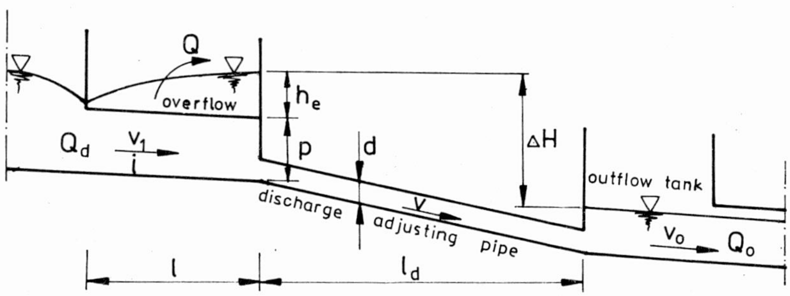

Fig. 1. Diagram of lateral overflow with a discharge adjusting pipe

From the hydraulic point of view, the discharge adjusting pipe (fig. 1) acts as a siphon. Energy loss ΔH during flow through the pipe may be defined as

$$\Delta H = \zeta \frac{v^2}{2g} + \lambda \frac{l_d}{d} \frac{v^2}{2g} + \frac{v^2}{2g}. \tag{6}$$

The terms included in the right-hand side of eq. (6) describe energy losses at the inlet, along the length, and at the outlet of the adjusting pipe, respectively, when

$$\frac{\alpha_0 v_1^2}{2g} \approx 0 \quad \text{and} \frac{\alpha_0 v_0^2}{2g} \approx 0.$$

Equation (6) may be reduced to the form

$$\Delta H = \frac{v^2}{2g}(1+\zeta_c), \tag{7}$$

where

$$\zeta_c = (\zeta + \lambda\, l_d/d).$$

Using eq. (7), we can calculate the mean flow velocity $\bar{v}$

$$\bar{v} = \sqrt{\frac{2g\,\Delta H}{1+\zeta_c}} \tag{8}$$

and the efficiency for the adjusting pipe (by virtue of the continuity law):

$$Q_0 = F\,v = \mu_d F \sqrt{2g\,\Delta H} \tag{9}$$

where F is the surface area of the pipe cross-section, m^2, and μ_d is the discharge coefficient which takes the form

$$\mu_d = \sqrt{\frac{1}{1+\zeta_c}}.$$

After simplification we obtain

$$Q_0 = C\sqrt{\Delta H}, \tag{10}$$

where $C = \mu_d F \sqrt{2g}$.

3. SIMILARITY SCALE

To create favourable conditions for the mechanical similarity of the phenomena occurring in the model and in nature it is necessary to preserve the geometrical, kinematic and dynamic similarity. Geometrical similarity is preserved when adopting a constant length scale ξ_l for all linear dimensions (l, p, h, ...). Kinematic similariry is based on the time scale ξ_t, which depends on the assumed dynamic similarity criterion.

Considering the Froude criterion, we find that

$$\xi_t = \xi_v = \xi_l^{0.5}. \tag{11}$$

Using the law of continuity of motion, we obtain

$$\xi_Q = \xi_l^{2.5}. \tag{12}$$

Hence,

$$Q_N = \xi_l^{2.5} Q_M. \tag{12a}$$

This is the fundamental formula enabling model scale/natural scale conversion of flow. It should be added that hydraulic gradient and pressure head are modelled at 1:1 scale and ξ_l scale, respectively.

The hydraulics of the discharge adjusting pipe (described by eq. (10)) may be written as

$$\xi_{Q_0} = \xi_C \, \xi_{\Delta H}^{0.5}. \tag{13}$$

Hence,

$$\xi_C = \xi_l^2 \tag{14}$$

and

$$C_N = \xi_l^2 C_M. \tag{14a}$$

Knowing the coefficient C_N, we can convert the hydraulic effect of adjustment from model to actual (natural) conditions. When placing the inlet channel before the overflow, it is necessary to consider friction forces which are responsible for linear losses. Linear losses in the sewer system are calculated in terms of the Manning formula for mean flow velocity. Hence, we can write (fig. 1):

$$\xi_{v1} = \frac{1}{\xi_n} \xi_{R_h}^{2/3} \xi_i^{1/2} \tag{15}$$

or

$$\xi_{v1} = \frac{1}{\xi_n} \xi_l^{2/3} \tag{16}$$

when $\xi_i = 1$ and $\xi_{R_h} = \xi_l$.

Using the Froude criterien $\xi_{v1} = \xi_l^{1/2}$ and comparing both scales of velocity we obtain

$$\frac{1}{\xi_n} \xi_l^{2/3} = \xi_l^{1/2}. \tag{17}$$

Hence,

$$\xi_n = \xi_l^{1/6} \tag{18}$$

and

$$n_N = \xi_l^{1/6} n_M. \tag{18a}$$

Making use of eq. (18a), we may conclude whether or not the linear losses in the model are adequate to those in the actual system.

4. STORM OVERFLOW MODEL STUDIES

The study was conducted in the laboratories of the Institute of Environment Protection Engineering, Technical University of Wrocław [2], [4]. Special consideration was given to the measuring methods and to the interpretation of measured data.

The objective of the study was a better understanding and mathematical description of the hydraulic phenomena involved in single overfall edge or double overfall edge systems. Measurements were carried out on a $\xi_l = 15$ geometrical scale model (fig. 2). The model consisted of an inlet channel (5.0 m long, in nature 75.0 m) with an overflow tank at its end. The channel had a rectangular section (0.10 m wide and 0.15 m high, in nature 1.5 m and 2.25 m, respectively) and was made of organic glass. The baffles of the overflow tank were 0.10, 0.20 and 0.30 m long in the model (l_M) and 1.5, 3.0 and 4.5 m long in nature (l_N). They were parallel to the bottom and were raised to the height of $p_M = 0.025$, 0.050 and 0.075 m ($p_M = 0.375$, 0.750 and 1.125 m). The study involved nine variations of the baffle parameters. The symmetry of the double overfall edge system was kept constant. Water flow rate Q_d in the inlet channel was varied in a discrete manner (fig. 3).

A 30-mm diameter (in nature 0.450 m) rubber conduit and a valve on the front wall of the overflow tank were designed to control the outflow Q_0. The rubber conduit was connected to the outflow tank. Outflow was varied in a discrete manner (the first variant (fig. 3) being conducted at $Q_0 = 0$).

The roughness coefficient for the inlet channel n, included in the Manning formula, was evaluated by model balancing. Thus, $n_M = 0.0089$, and by virtue of (18a) $n_N = 0.014$ (which is consistent with the actual conditions).

The numerical value of the coefficient C for the discharge adjusting pipe (included in eq. (10)) amounts to $C_M = 8.84 \times 10^{-4} \mathrm{m}^{2.5}/\mathrm{s}$. Hence, by virtue of eq. (14a), $C_N = 0.199\ \mathrm{m}^{2.5}/\mathrm{s}$.

Measurements in the model were conducted after flow steadying and included water temperature, rate of water inflow to the channel Q_d, performance of the overflow Q, water discharge through the adjusting pipe Q_0, behaviour of the water table in the channel axis and above the overfall edges, and head loss ΔH. Head loss

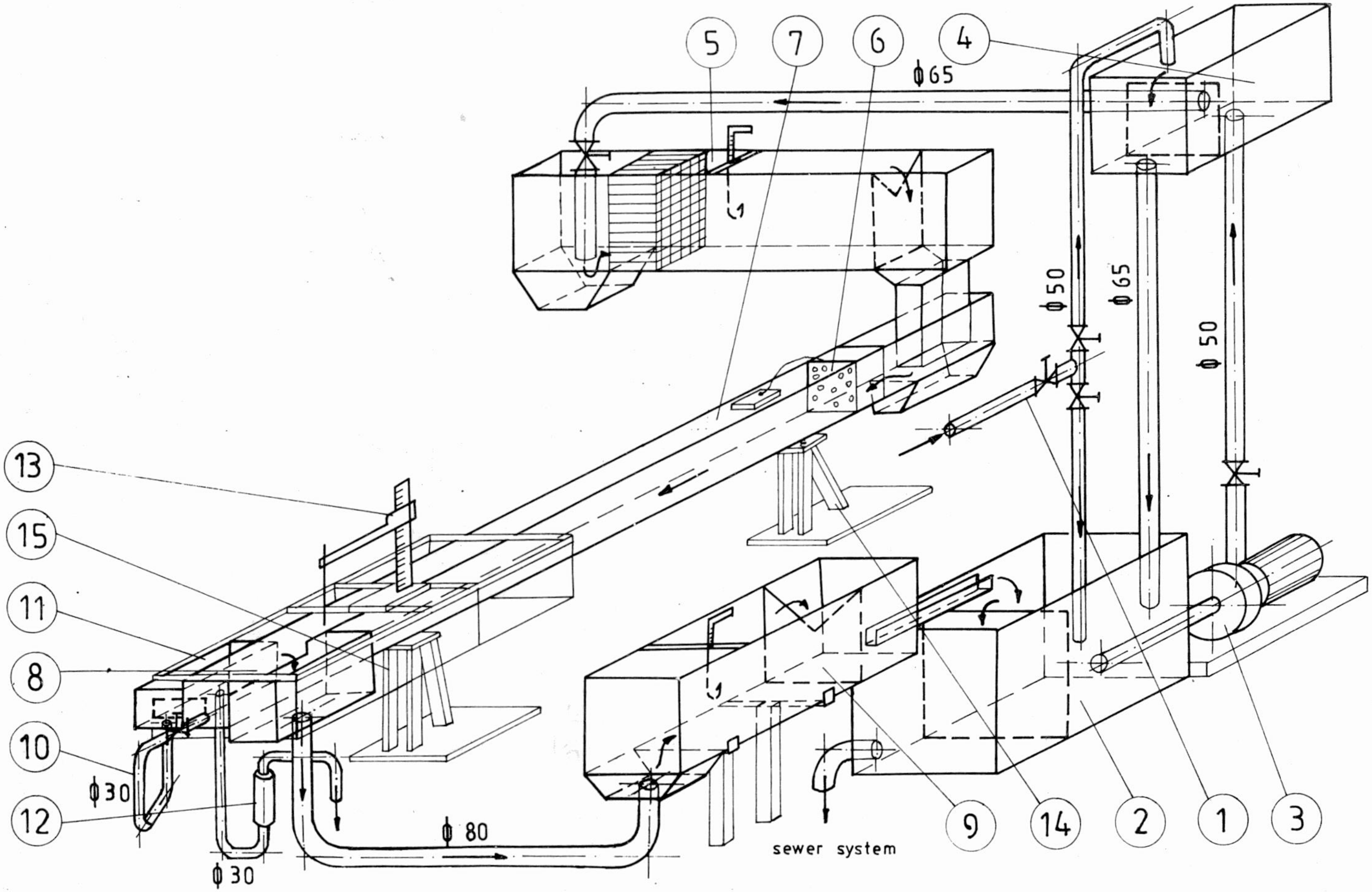

Fig. 2. Experimental system

1 – inlet, *2* – recirculating tank, *3* – pump, *4* – constant head tank, *5* – triangular overfall at inflow, *6* – flow steadying tank, *7* – inlet channel, *8* – overflow tank with removable baffles, *9* – triangular overfall at outflow, *10* – discharge adjusting pipe, *11* – outlet tank, *12* – rotameter, *13* – penetrometer, *14* – adjustable support, *15* – support

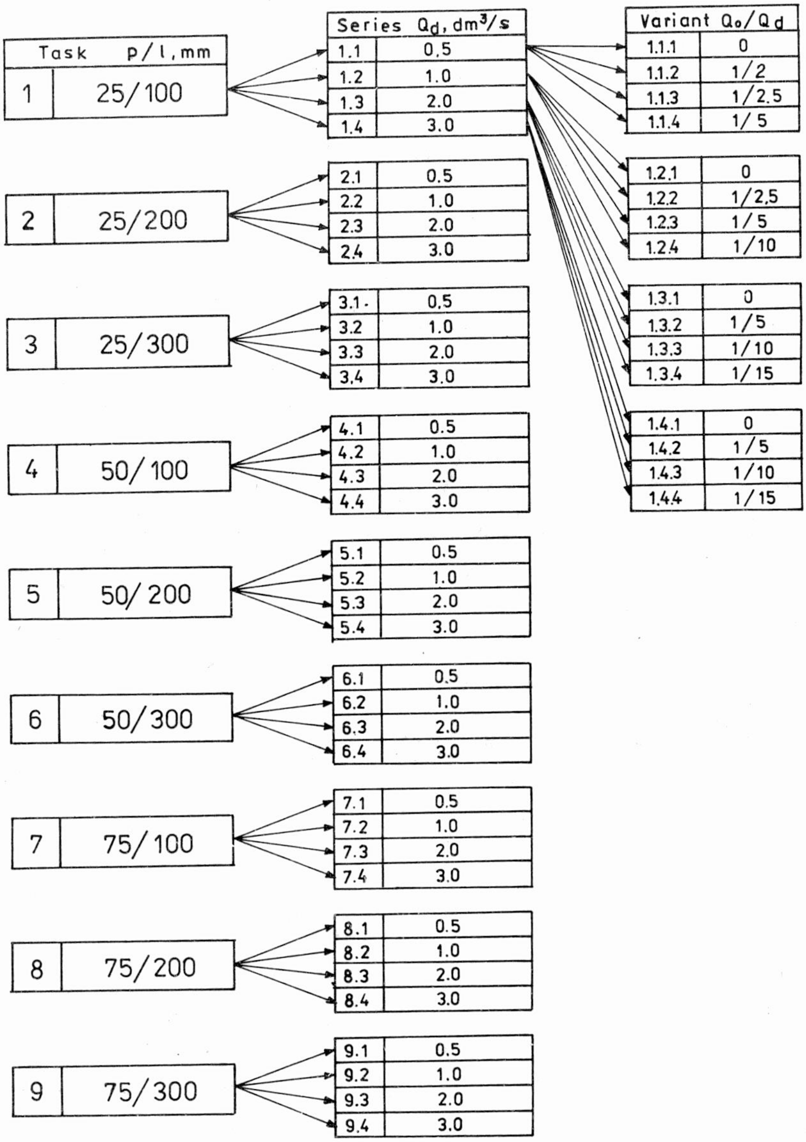

Fig. 3. Scheme of measurements

was determined from the difference in the water table between the outflow tank and the overflow tank (fig. 1).

Model investigations have revealed three behavioural patterns in the overflow with regard to the shape of the water table above the overfall edges (fig. 4): Pattern A, steady flow; Pattern B, transient flow, and Pattern C, turbulent flow. In spite of this, water passing through the inlet channel moved in a steady flow. The investigations

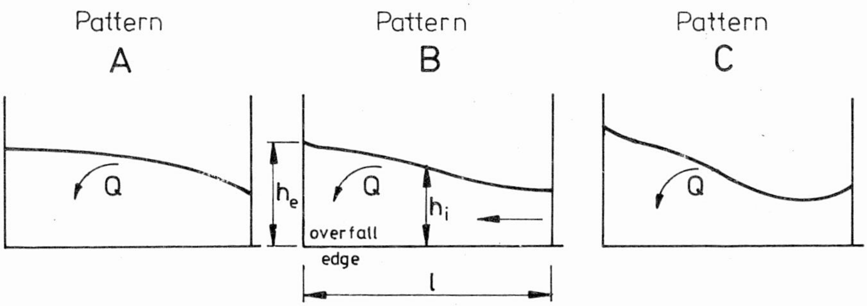

Fig. 4. Behavioural patterns in lateral overflow

reported in [2] and [4] have led to the following findings: 1) bottom sloping i is without any effect whatsoever on the performance of the overflow, and 2) the baffle position p has a slight effect on the h_i value. Thus, the two parameters have been neglected in this study.

When interpreting the measured results for the double overfall edge system, it has been assumed that the height h of eqs. (4) and (5) is equivalent to the height h_e (at the ends of the overfall edge (fig. 4)) and that the performance of the two overfall edges is identical and equals $Q/2$. Thus, eq. (4) and eq. (5) become [4]

$$y = f(x) \tag{19}$$

where

$$y = \frac{Q}{2g^{0.5}\,h_e^{2.5}}, \qquad x = \frac{l}{h_e}$$

and

$$\frac{Q}{2g^{0.5}\,h_e^{2.5}} = a\left(\frac{l}{h_e}\right)^b. \tag{20}$$

Equation (20) has the following logarithmic form:

$$\lg y = \lg a + b\lg x. \tag{21}$$

A separate linear description of the relation (21) has been adopted for Patterns A, B and C. Numerical calculations enabled establishing three straight line equations in binary logarithmic system (figs. 5, 6 and 7). The significance and the level of linear correlation (R and α) were also examined. The lines of figs. 5, 6 and 7 have been obtained at the following l/h_e variations in the model:

$3.91 \leqslant l/h_e \leqslant 70.59$, Pattern A (fig. 5),
$2.69 \leqslant l/h_e \leqslant 16.22$, Pattern B (fig. 6),
$2.19 \leqslant l/h_e \leqslant 15.71$, Pattern C (fig. 7).

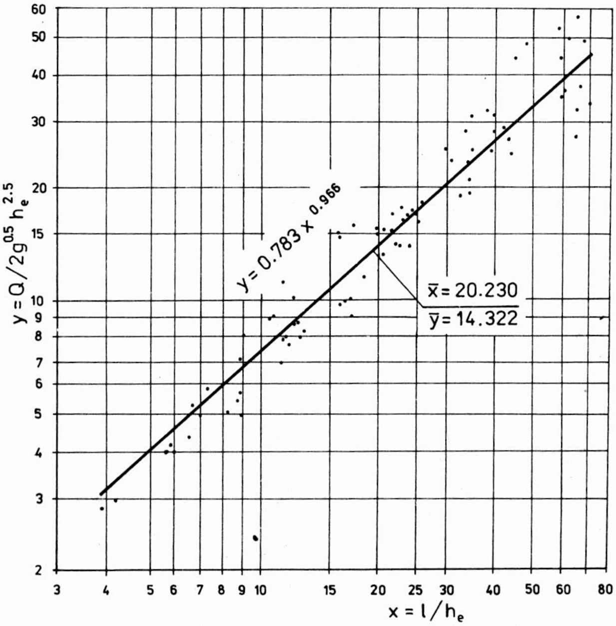

Fig. 5. $y = Q/2g^{0.5}\ h_e^{2.5}$ versus $x = l/h_e$ (Pattern A)
$y = ax^b$, $a = 0.783$, $b = 0.966$, $R = 0.975$, $\alpha = 0.001$

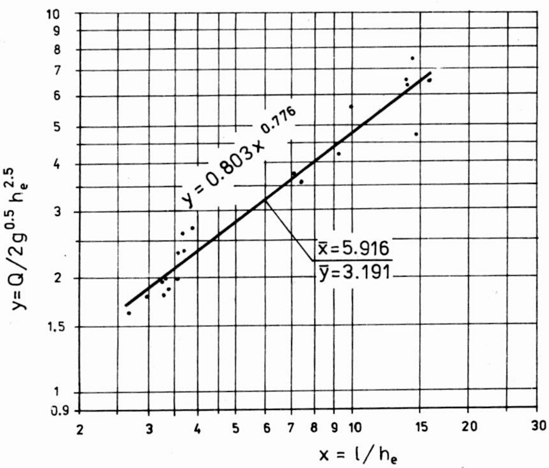

Fig. 6. $y = Q/2g^{0.5}\ h_e^{2.5}$ versus $x = l/h_e$ (Pattern B)
$y = ax^b$, $a = 0.803$, $b = 0.776$, $R = 0.976$, $\alpha = 0.001$

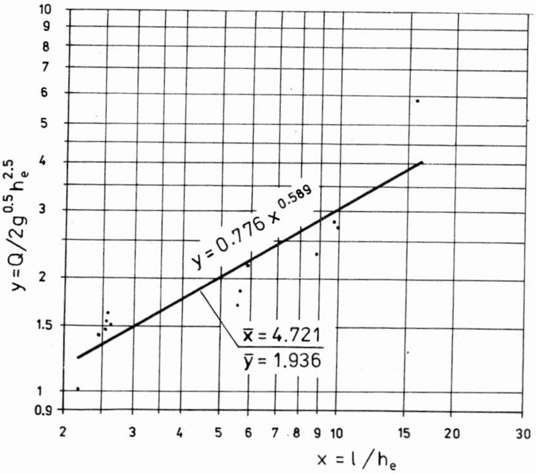

Fig. 7. $y = Q/2g^{0.5}\ h_e^{2.5}$ versus $x = l/h_e$ (Pattern C)
$y = ax^b$, $a = 0.776$, $b = 0.589$, $R = 0.909$, $\alpha = 0.001$

The limitations, that have to be considered when applying the formulae derived in this study to natural operating conditions, are as follows:

$0.43 \leqslant Q_d \leqslant 2.61\ \mathrm{m^3/s}$,
$0.21 \leqslant Q \leqslant 2.61\ \mathrm{m^3/s}$,
$1/15 \leqslant Q_0/Q_d \leqslant 1/2$.

5. CONCLUSIONS

1. Dimensional analysis enables formulation of physical expressions for the performance of lateral overflow with discharge adjustment. The numerical values of the coefficients included in these formulae could be established by investigations on a hydraulic model.

2. In model investigations of lateral overflows, force of gravity and force of internal friction should be regarded as dominant. The dynamic similarity of the phenomena involved in the model and in nature consists in satisfying the Froude criterion and taking into account the Manning formula. When these requirements are fulfilled, the physical quantities of the model can be fitted to natural conditions by making use of an appropriate similarity scale.

3. The methods proposed may be of utility in model investigations of any other object belonging to the sewer system (e.g., separators).

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METODOLOGICZNE PODSTAWY BADAŃ MODELOWYCH PRZELEWÓW BURZOWYCH

Sformułowano podstawy metodologiczne badań na modelach hydraulicznych przelewów bocznych z regulowanym, za pomocą rury dławiącej, odpływem ścieków do oczyszczalni. Zastosowanie teorii podobieństwa mechanicznego i analizy wymiarowej zjawiska pozwoliło na wyprowadzenie wzorów fizykalnych na wydajność przelewu. Pomiary prowadzono na modelu w skali geometrycznej 1:15. Omówiono wybrane wyniki badań modelowych przelewu jedno- i dwustronnego. Odniesiono wyniki tych badań do skali rzeczywistej.

МЕТОДОЛОГИЧЕСКИЕ ОСНОВЫ МОДЕЛЬНЫХ ИССЛЕДОВАНИЙ ЛИВНЕСПУСКОВ

В работе сформулированы методологические основы исследований моделей гидравлических боковых водосливов с регулируемым при помощи дроссельной трубы стоком сточных вод к очистной станции. Применение теории механического подобия и размерного анализа явления позволило вывести физические формулы эффективности водослива. Измерения вели на модели в геометрической шкале 1:15. Обсуждены избранные результаты модельных исследований одно- и двухстороннего переливов. Результаты этих исследований сравнены с результатами в реальной шкале.