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STANISŁAW BIEDUGNIS*

MATHEMATICAL MODEL OF THE PRESSURE SEWERAGE SYSTEM FOR DESIGN PURPOSES AND ANALYSIS OF ITS OPERATION

Pressure sewerage system is one of the most recent solutions to the problems of sewage disposal.

The paper presents a mathematical model that can be used in solving design and exploitation problems related to the pressure sewerage system. A special attention has been paid to the following problems: 1. total hydraulic analysis of the pressure sewerage system, 2. the problems of hydraulic calculation of pressure sewerage system, 3. mathematical model for the design purposes and analysis of the operation of pressure sewerage systems.

The scope of the present paper covers branched network systems, assuming that hydraulic characteristics of their technical components are given. The total hydraulic analysis of the pressure sewerage system operation has been performed by Freeman's graphical method. This method consists in graphical solving of the set of nonlinear algebraic equations. Considering, however, the fact that this method is time-consuming a mathematical model has been developed according to which the problems formulated on the basis of a general hydraulic analysis could be solved. This model was based on the assumption that in hydraulically long conduits filled completely with sewerage, the pressure flow is forced by pumps.

DENOTATIONS

a_i — hydraulic characteristics of the aggregate,
a_i^{-1} — reverse hydraulic characteristics of the aggregate,
$a_{j,1}$, $a_{i,2}$ — data describing the hydraulic characteristics of the aggregate,
d_i — internal diameter of the conduit(mm),
d'_i — the assumed internal diameter of the conduit (mm),
g — acceleration of gravity (m/s²),
h — length of interval (m),
h_i — hydraulic characteristics of the branch,
h_i^{-1} — reverse hydraulic characteristics of the branch,

* Institute of Water Supply and Hydrotechnics of the Technical University of Warsaw, 00-661 Warsaw, pl. Jedności Robotniczej 1.

h_i^g — total hydraulic characteristics of branches,
h_{Ri} — hydraulic losses in the main conduit (m),
h^{sg} — total hydraulic characteristics of the branches operation,
h_p^{sg} — total hydraulic characteristics of the operation of pressure sewerage system tree,
h_i' — hydraulic losses in small conduit (m),
i — index of conduits (nodes) of the network,
i_s — small conduit at the sucking side of the aggregate,
i_t — small conduit at the pumping side of the aggregate,
j — index of the hydraulic characteristics point,
k — number of aggregates,
k_i — roughness of the conduit internal walls (mm),
l_i — length of the conduit (m),
m — number of subintervals,
m' — length of time interval of the aggregate tank emptying (min),
n — number of aggregates (small conduits) or segments of the main conduit,
n' — length of time interval of the aggregate tank filling up (min),
n'' — number of points determining the aggregate characteristics,
p — number of conduits (nodes) of the network,
p' — probability of the event X_i,
q — probability of the event X'_i,
r — number of aggregates operating simultaneously,
r_i — hydraulic characteristics of the conduit,
r_i^{-1} — reverse hydraulic characteristics of the conduit,
v_i — mean selfpurification velocity (m/s),
v_{ri} — difference of the mean real and selfpurification velocity (m/s),
v_{rzi} — mean real velocity (m/s),
w_i — node number,
z_i — ordinate of the sewage level in the aggreagte tank (m),
zlc_i — ordinate of the pressure line (m),
z_w — ordinate of the sewage level at treatment plant inlet (m),
A_i — pressure-tank aggregate,
D — pressure sewerage system tree,
DP — basic tree of pressure sewerage system,
G — branch of pressure sewerage system,
H_i — overpressure with respect to the assumed reference level (m),
H_g — initial value of the limiting pressure (m),
H_{gri} — limiting overpressure (m),
$H_{\max}$ — maximal value of overpressure (m),
H_{ui} — useful lifting height of the aggregate (m),
N — number of branches,
P — conduit of pressure sewerage system,
$P(R)$ — probability of the event R,
$P(\bar{R})$ — probability of the event $\bar{R}$,
Q_i — flow intensity (dm^3/s),
Q_j — aggregate output (dm^3/s),
$Q_{\max}$ — maximal value of flow intensity (dm^3/s),
Qwi — flow intensity in mode (dm^3/s),
R — event of a simultaneous emptying of r tanks,
$\bar{R}$ — opposite event R,

Re — Reynolds number,
R_i — segment of the main conduit,
S — set of commercial diameters (mm),
T — time at which more than k aggregates will operate (years),
X_i — event of the aggregate tank emptying,
X_i' — event of the aggregate filling,
W — pressure sewerage system node,
Z_i — ordinate of overpressure in auxiliary piezometer (m),
Z_{it} — ordinate of overpressure in auxiliary piezometer connected to the pressure conduit of the small conduit (m),
ϱ_k — coefficient of local hydraulic resistance,
λ_i — coefficient of linear hydraulic resistance,
ν — kinematic coefficient of sewage viscosity (m^2/s),
π — pi number,
Ω, Ω' — determinacy sets of characteristics.

1. SUBJECT, PURPOSE, AND SCOPE OF THE PAPER

Pressure sewerage system is one of the most recently developed solutions in the domain of sewage disposal [2, 4–7, 11–13, 19, 20].

The purpose of the paper is to present a mathematical model useful in solving the design and operation problems related to pressure sewerage system. The paper deals with branched systems, assuming that hydraulic characteristics of the systems' components are given. Ring systems and the problems concerning detailed technical solutions of the sewerage system, as well as the optimization problems are beyond the scope of the paper.

2. GENERAL HYDRAULIC ANALYSIS OF THE PRESSURE SEWERAGE SYSTEM

Pressure sewerage systems consist of hydraulic elements which cooperate with one another, namely: tank-pumping aggregates (feeding sources), pressure laterals, and pressure mains. The total hydraulic analysis of pressure sewerage operation based on Freeman's graphic method [1, 8–10, 14–18] was performed for the hydraulic system (fig. 1) containing n pumping aggregates the characteristics of which are given. The aggregates are equipped with tanks, the sewage levels in these tanks being established on the levels z_i, where $i = \overline{1, n}$. Operation of the pressure sewerage system runs as follows: the tanks of the pumping aggregates are filled from the domestic gravity sewerage system, thereupon the tank is emptied and the sewage forced through a pressure lateral channel into the pressure main conduit. Automatic start of the aggregates results in a pulsatory flow through the pipes. Thus, the number of the pumping aggregates operating simultaneously at the given time may be determined with a defined probability. In the case, considered as an example, there are n aggregates operating simultaneously. The dimensions of all the pipes are given and the values of Q_i and H_{ui}, where $i = \overline{1, n}$, should be determined. In order to facilitate the geometrical interpretation of the above case, the auxiliary piezometers have been presented in fig. 2.

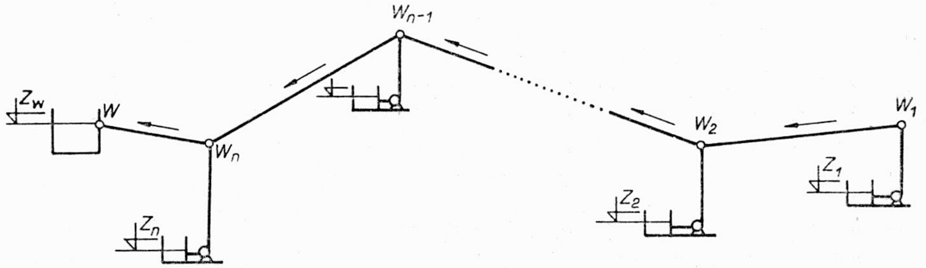


Fig. 1. Hydraulic system assumed in analysis of the pressure sewerage system operation
Rys. 1. Hydrauliczny układ przyjęty do analizy układu ciśnieniowej sieci kanalizacyjnej

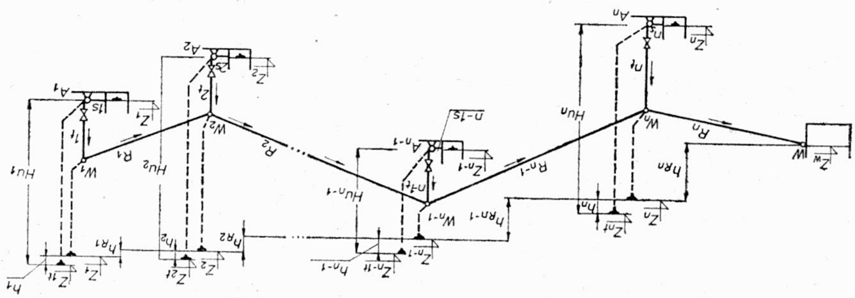


Fig. 2. Distribution of pressures in nodes for hydraulic system presented in fig. 1
Rys. 2. Rozkład ciśnień w węzłach dla hydraulicznego układu przedstawionego na rys. 1

The equations of the balances of flows through the nodes are the following:

$$Q_{wi} = \sum_{j=1}^{i} Q_j \quad \text{for } i = 1, 2, \ldots, n. \tag{1}$$

Using Bernoulli's equation we get for the separate pipes the following set of equations:

$$H_{ui} = Z_i - z_i + h'_i \quad \text{for } i = 1, 2, \ldots, n, \tag{2}$$

$$Z_i - Z_{i+1} = h_{Ri} \quad \text{for } i = 1, 2, \ldots, n-1, \tag{3}$$

where

$$h'_i = \left(\sum_k \varrho_k + \lambda_i \frac{l_i}{d_i}\right) \frac{8Q_i^2}{\pi^2 g d_i^4} \quad \text{for } i = 1, 2, \ldots, n \tag{4}$$

and

$$h_{Ri} = \lambda_i \frac{l_i}{d_i} \frac{8Q_{wi}^2}{\pi^2 g d_i^4} \quad \text{for } i = 1, 2, \ldots, n. \tag{4'}$$

Solution of the equation 1–3 is reduced to solution of n linear algebraic equations 1 and $2n$ nonlinear algebraic equations 2–3, where Q_{wi}, Q_j, H_{ui}, Z_i are unknowns. The system of equations 1–3 with $4n$ unknowns has been completed graphically with the given characteristics of the pumping aggregates:

$$a_i = f_i(Q_i) \quad \text{for } i = 1, 2, \ldots, n. \tag{5}$$

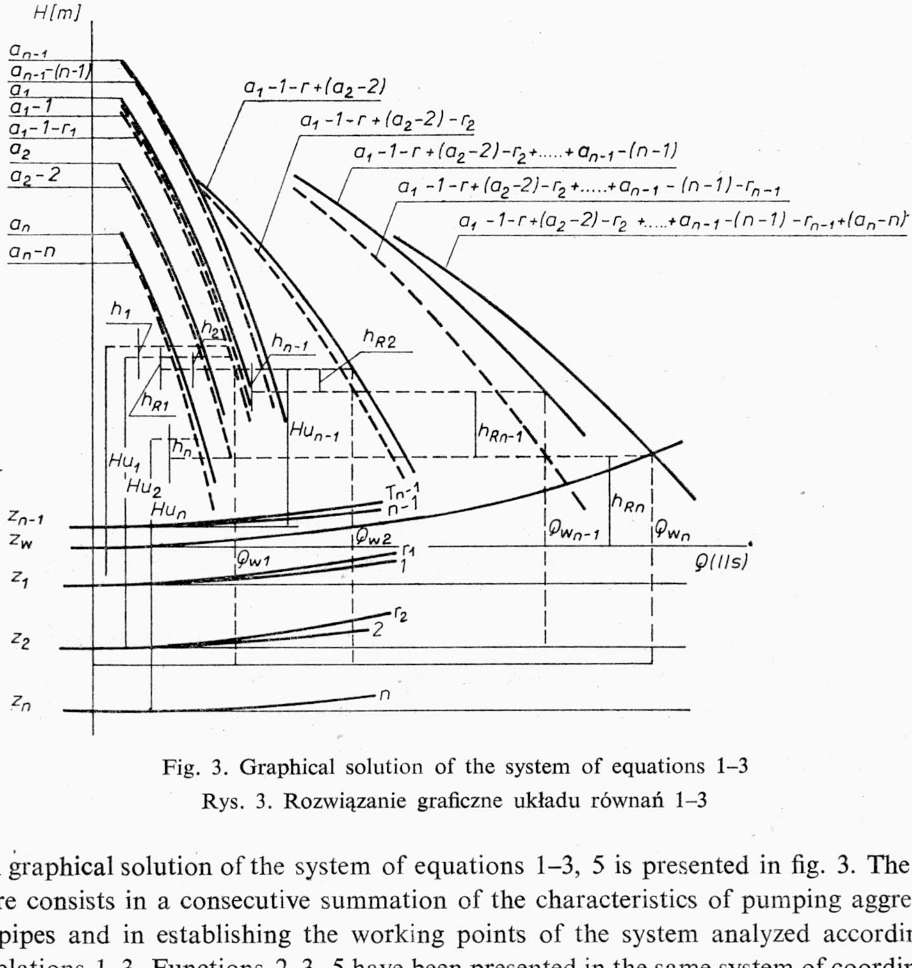


Fig. 3. Graphical solution of the system of equations 1–3

Rys. 3. Rozwiązanie graficzne układu równań 1–3

A graphical solution of the system of equations 1–3, 5 is presented in fig. 3. The procedure consists in a consecutive summation of the characteristics of pumping aggregates and pipes and in establishing the working points of the system analyzed according to the relations 1–3. Functions 2–3, 5 have been presented in the same system of coordinates.

3. PROBLEMS CONNECTED WITH A HYDRAULIC CALCULATION OF A PRESSURE SEWERAGE SYSTEM

Design of the pressure sewerage system is based on the following data: topography of the ground, site planning, type and series of the tank-pumping aggregates, and location of wastewater treatment plant. The above data are used to set up the location of conduits and to choose the aggregates and diameters of pipes. In case when there exists a pressure sewerage system the following problems may arise: a new feeding source may be added and its operation parameters should be established, the parameters of the existing feeding sources may be changed, the necessary extension of the sewerage system, etc.

To solve the above tasks the following types of problems have been formulated for the hydraulic calculation of the sewerage considered:

PROBLEM 1

For the given pressure sewerage system consisting of:

1. r tank-pumping aggregates the characteristics and sewage levels z_i, where $i = \overline{1, r}$ being given, and of

2. p pipes determined preliminary by d_i', l_i, k_i, where $i = \overline{1, p}$, the diameters d_i of the pipes should be selected from the available set S of the commercial diameters having in mind that the given rate of selfpurification in the pipe should be achieved and the overpressure in node be not exceeded.

PROBLEM 2

For the given pressure sewerage system composed of:

1. p tank-pumping aggregates the characteristics and sewage levels z_i, where $i = \overline{1, p}$ being given, and of

2. p pipes determined by d_i, l_i, k_i, where $i = \overline{1, p}$ determine the flow intensities Q_i and useful pumping heights of the aggregates H_{ui}, where $i = \overline{1, p}$.

The problems of the type I refer to design tasks, those of the type II — to the operation.

4. MATHEMATICAL MODELLING OF THE PRESSURE SEWERAGE SYSTEM FOR DESIGNING AND OPERATIONAL PURPOSES

Considering the fact that the hydraulic systems of the sewerage are usually very large and that Freeman's graphical method is tedious and time-consuming, a mathematical model should be developed to solve the above formulated problems. This model was based on the following assumptions:

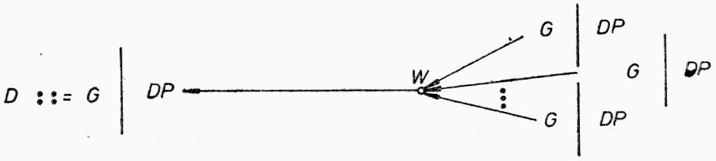
in hydraulically long pipes the flow is forced with pumps,

the motion is continuous, steady, and isothermic,

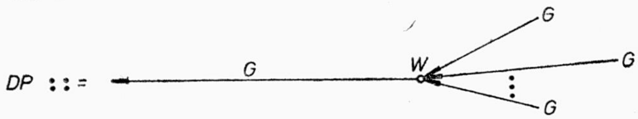
the characteristics of the pumping aggregates are shifted vertically with respect to the assumed reference level on the ordinate z_w of the outlet to the treatment plant.

The systems of the sewerage considered should satisfy the following conditions: in each pipe the selfpurification velocity v_i should be achieved once a day (24 h), and maximal overpressure in the most distant or the lowest point (i. e. most disadvantageous) of the network should not exceed the limiting value H_{gri} more often than every T years.

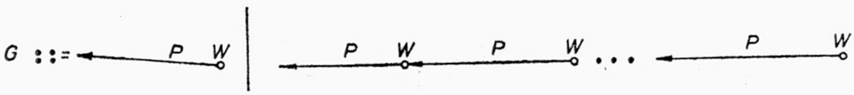
For the above assumptions and basing on the laws of the theory of graphs, algebra and probability calculus, the following mathematical model has been constructed:



where:



Basic tree *DP* denotes a set of branches reaching a common node *W* and one branche originating from this node.



Branch *G* denotes the conduit *P* ended with node or an alternative sequence of conduits and nodes beginning with a conduit and ending with a node.

P : : = ————————————

By a conduit we mean a segment connecting two nodes in the network W : : = ○. By a node we mean each characteristic point of the network. By a pressure tree of sewerage system we mean each coherent oriented graph which does not include cycles.

Nodes in which there appears an aggregate are described by the characteristics (5), whereas the conduits are described by the characteristics $r_i = f_i(Q_i)$, where $i = \overline{1, p}$. The characteristics a_i and r_i are defined within the interval $\Omega = [O : Q_{\max}]$. The flow intensity $Q_{\max}$ is the flow caused by a simultaneous operation of the maximal number of the pumping aggregates in the time interval T. Characteristics of aggregates used in pressure sewerage system are continuous and monotonic. The characteristics of conduits are monotonic and their continuity may be obtained by coupling their segments in the points corresponding to Re = 2320 and Re = 4000. Hence, it follows that there exists reverse characteristics: $a_i^{-1} \in C[\Omega']$ and $r_i^{-1} \in C[\Omega']$, where $\Omega' = [O : H_{\max}]$.

In order to determine the characteristics of cooperation of the separate elements of the pressure sewerage tree, the following operations have been introduced to the set of characteristics:

operation $\oplus$ equivalent to the common addition of characteristics a_i^{-1}, where $i = \overline{1, p}$ in the set Ω,

operation $\ominus$ equivalent to the common substraction of characteristics a_i, r_i, where $i = \overline{1, p}$ in the set Ω,

operation $\boxed{+}$ equivalent to common addition of reverse characteristics of the cooperation of the branch h_i^{-1}, where $i' = \overline{1, N}$ in the set Ω'.

The characteristics of cooperation between the separate elements of the pressure sewerage tree have been determined by means of the following recurrent relationships:

$$h_{2i-1} = \begin{cases} a_i \ominus r_i & \text{for } i = 1 \\ h_{2i-2} \ominus r_i & \text{for } 1 < i \leqslant n-1, \end{cases} \tag{6}$$

$$h_{2i} = \begin{cases} h_i \oplus a_{2i} & \text{for } i = 1 \\ h_{2i-2} \oplus a_{i+1} & \text{for } 1 < i \leqslant n-1, \end{cases} \tag{7}$$

$$h^{sg} = h_1^g \boxed{+} h_2^g \boxed{+} \ldots \boxed{+} h_N^g. \tag{8}$$

Working points of the pressure sewerage tree have been determined with the help of the following relations:

working point 1

$$\begin{cases} h_p^{sg}(Q_1) = r_1(Q_1), \\ H_{u1} = r_1(Q_1), \end{cases} \tag{9}$$

the remaining working points

$$h_{2i-1}(Q_i) = H_{ui+1} \quad \text{for } i = 1, 2, \ldots, p-1, \tag{10}$$

$$H_{ui} = \begin{cases} h_{2i-2}(Q_i) & \text{for } i = 1, 2, \ldots, p-1 \\ a_i(Q_i) & \text{for } i = p. \end{cases} \tag{11}$$

The operation of the pressure sewerage system consists in an automatic start of the pumping aggregates, occurring periodically. The moments at which the aggregates start operating depend exclusively on the filling up of their tanks, whereas the operation time of an aggregate is the function of the tank volume, hyperpressure, and the aggregate characteristics.

Considering the fact that the pressure in the sewerage system is subject to rapid changes, it is very difficult to establish in detail the duration of the operation cycles of the aggregates. Therefore to determine the probability of a simultaneous operation of aggregates it has been assumed that the duration of an operation cycle corresponds to the overpressure in the sewerage system. This probability was calculated in the following way:

let m' denotes the time interval in which the aggregate tank is emptied (min), n' denotes the time interval in which the aggregate tank is filled up (min), and k denotes the number of aggregates calculated from the size of settling unit. For X_i denoting the event, consisting in fact that the tank of the i-th aggergate is being emptied at the given moment, the probability of this event is

$$p' = P(X_i) = \frac{m'}{m'+n'} \quad \text{for } i = 1, 2, \ldots, k, \tag{12}$$

whereas the probability of the event X_i', consisting in fact that at the given time moment the i-th aggregate tank is being filled, is:

$$q = P(X_i') = \frac{n'}{m'+n'} \quad \text{for } i = 1, 2, \ldots, k. \tag{13}$$

By R we denote the probability that at the given time moment r tanks ($r \leqslant k$) are being emptied. The probability of this event is:

$$P(R) = P_k(1)+P_k(2)+ \ldots +P_k(r-1)+P_k(r)$$
$$= \binom{k}{0} p^0 q^k + \binom{k}{1} p^1 q^{k-1} + \ldots + \binom{k}{r} p^r q^{k-r}, \tag{14}$$

whereas the probability of an opposite event $\bar{R}$, consisting in fact that at the given time moment more than r aggregates will operate simultaneously, is

$$P(\bar{R}) = 1-P(R). \tag{15}$$

The value m', $m' \ll n'$, has been assumed as an elementary time unit. Thus, it may be assumed that $P(\bar{R})$ is the estimate of the frequency of the event $\bar{R}$. Hence, on the average, the event $\bar{R}$ will will take place every

$$T = \frac{1}{P(\bar{R}) \times 525600} \text{ years}. \tag{16}$$

Starting with the mathematical model formulated in the way presented above, the algorithm and programmes of hydraulic calculation of the problems given in this paper have been worked out for the computer. A general block diagram of the algorithm for the solution of the type I problem is presented in fig. 4, the same for the problem of the type II being given in fig. 5.

The validity of the mathematical model has been verified by comparing the results of computer calculations and that obtained by graphical Freeman's method. From the comparison it follows that the upper limit of the absolute error does not exceed the value of 0.01. Thus, Q_i and H_{ui}, where $i = \overline{1, p}$, have been calculated with the accuracy of 0.01 dm^3/s and 0.01 m, respectively.

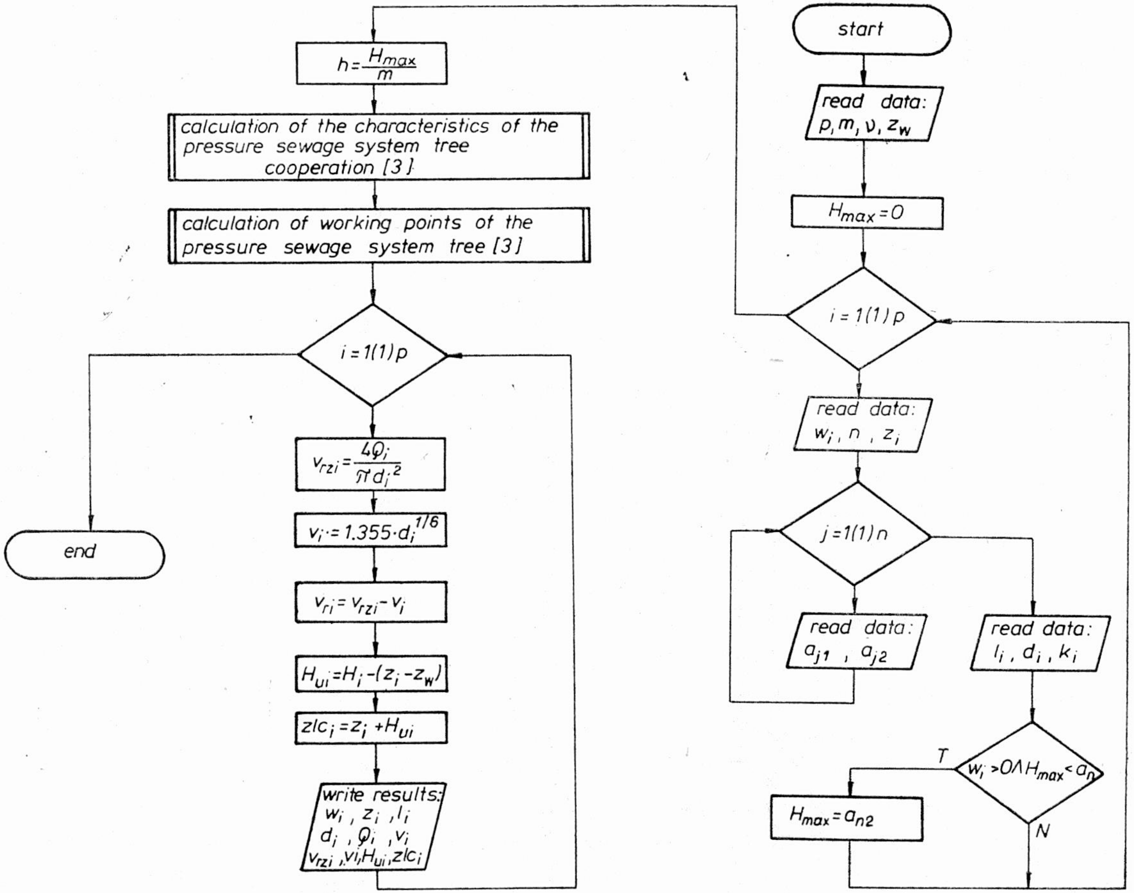


Fig. 4. General block diagram of the algorithm for the solution of the problem of the type I

Rys. 4. **Ogólny schemat blokowy algorytmu rozwiązania zadania I typu**

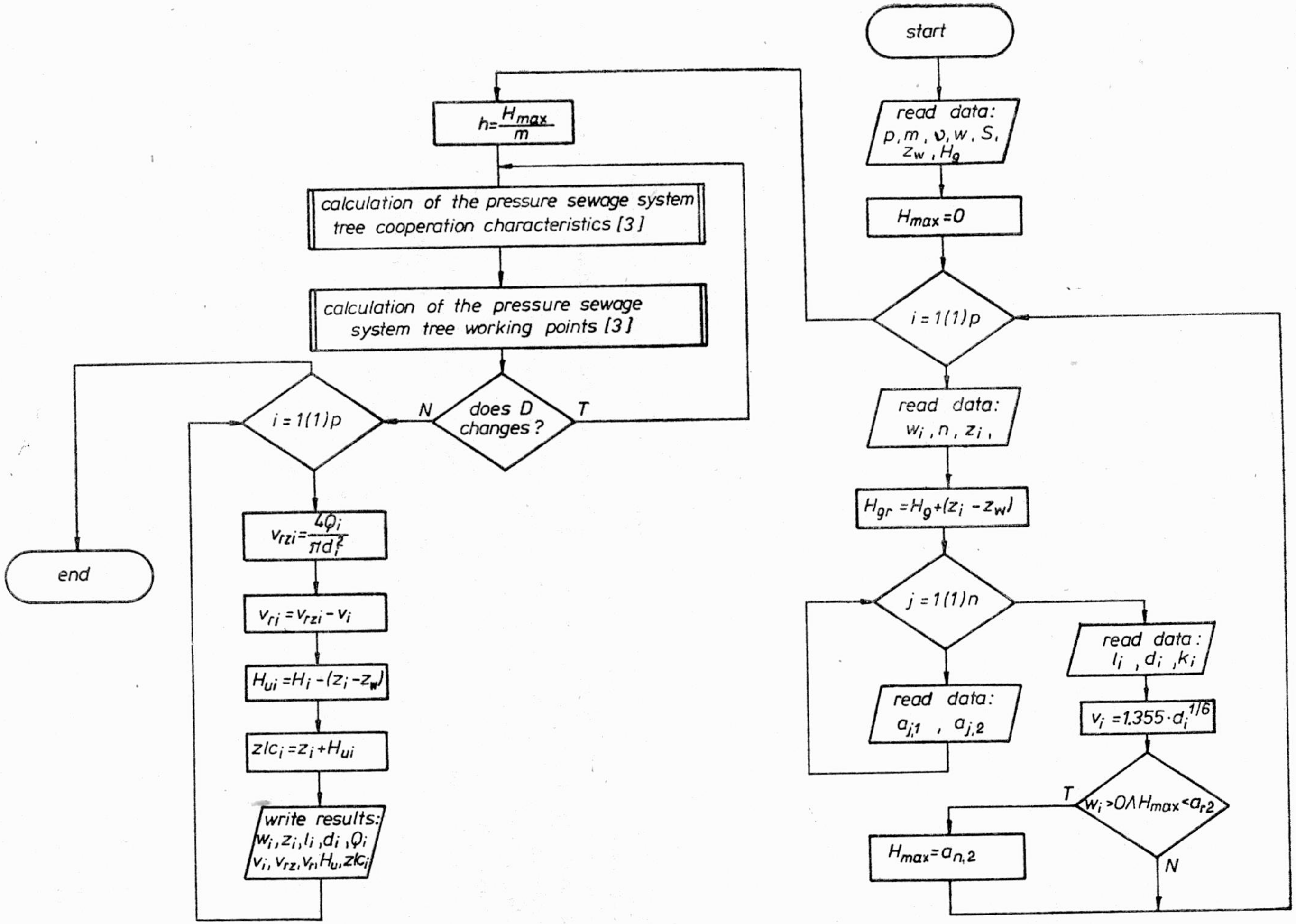


Fig. 5. General block diagram of the algorithm for the solution of the problem of the type IIc

Rys. 5. Ogólny schemat blokowy algorytmu rozwiązania zadania II typu

5. FINAL REMARKS

In view of the assumptions taken, the mathematical model presented in this paper describes the nature of phenomena occurring in pressure sewerage system, provided that the pipes are completely filled up with wastewater.

From the paper presented, some suggestions can be inferred concerning further research and investigations, of which the most important are the following:

mathematical model assuming the forced flow or the gravity one with a free water level,

mathematical model for ring systems,

introduction of optimization calculus into the problems considered.

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MODEL MATEMATYCZNY SIECI KANALIZACYJNEJ DLA POTRZEB PROJEKTOWANIA I ANALIZY JEJ DZIAŁANIA

Jednym z ostatnio rozwijanych rozwiązań w dziedzinie odprowadzania ścieków jest ciśnieniowa kanalizacja.

W opracowaniu przedstawiono model matematyczny przydatny do rozwiązywania zadań projektowych i eksploatacyjnych dotyczących ciśnieniowej kanalizacji ze szczególnym uwzględnieniem następujących fragmentów tego problemu: 1. ogólnej hydraulicznej analizy pracy układu ciśnieniowej kanalizacji, 2. zadania hydraulicznego obliczania ciśnieniowej sieci kanalizacyjnej, 3. modelu matematycznego dla potrzeb projektowania i analizy działania układów ciśnieniowej kanalizacji.

Zakresem opracowania objęto rozgałęzione układy sieciowe przy założeniu, że jego składowe elementy techniczne mają dane charakterystyki hydrauliczne. Do ogólnej hydraulicznej analizy działania układów ciśnieniowej kanalizacji zastosowano graficzną metodę Freemana. Metoda Freemana polega na graficznym rozwiązaniu układu algebraicznych równań nieliniowych. Uwzględniając jednak pracochłonność tej metody opracowano model matematyczny dla potrzeb rozwiązywania zadań sformułowanych na podstawie ogólnej hydraulicznej analizy. Model matematyczny sformułowano przy założeniu, że w całkowicie wypełnionych ściekami przewodach hydraulicznie długich występuje przepływ ciśnieniowy wymuszony pompami.

MATHEMATISCHES MODELL ZUR PROJEKTIERUNG UND ZUR ANALYSE DER ARBEITSWEISE EINES ENTWÄSSERUNGSNETZES

Zur Beseitigung von Abwasser wird in neuester Zeit auch die Druckentwässerung vorgeschlagen.

Der Beitrag beinhaltet ein mathematisches Modell einer Druckkanalisation mit spezieller Berücksichtigung: 1. einer allgemeinen hydraulischen Analyse der Arbeitsweise der Druckkanalisation, 2. der hydraulischen Berechnungsweise eines Drucknetzes und 3. eines mathematischen Modells für den Bedarf und zur Analyse der Arbeitsweise der Druckentwässerung.

Die Arbeit umfasst verästelte Netze mit der Annahme, daß alle Elemente einen hydraulischen Charakter haben. Zur allgemeinen hydraulischen Analyse des Drucknetzes wurde die graphische Methode von Freeman verwendet. Die Freeman'sche Methode baut auf graphischen Lösungen von algebraischen, nichtlinearen Gleichungen. Sie ist jedoch zeitaufwendig und aus diesem Grund wurde ein mathematisches Modell für den Bedarf der gestellten Aufgaben erarbeitet unter Bezug der allgemeinen hydraulischen Analyse. Das mathematische Modell formulierte man bei der Annahme, daß der Durchfluß in mit Abwasser voll gefüllten Langrohren durch Pumpen erzwungen wird.

МАТЕМАТИЧЕСКАЯ МОДЕЛЬ КАНАЛИЗАЦИОННОЙ СЕТИ ДЛЯ НУЖД ПРОЕКТИРОВАНИЯ И АНАЛИЗА ЕЁ ДЕЙСТВИЯ

Одним из развиваемых в настоящее время решений в области удаления сточных вод является напорная канализация.

В разработке предложена математическая модель, пригодная для решения проектных и эксплуатационных задач, касающихся напорной канализации с особенным учётом следующих фрагментов этой проблемы: I. общего гидравлического анализа работы системы напорной канализации, 2. задачи гидравлического расчёта напорной канализационной сети, 3. математической модели для нужд проектирования и анализа действия систем напорной канализации.

Пределы разработки охватывали разветвлённые сетевые системы при допущении, что его составные технические элементы имеют данные гидравлической характеристики. Для общего гидравлического анализа десйтвия систем напорной канализации был применён графический метод Фримана. Метод Фримана состоит в графическом решении системы алгебраических нелинейных уравнений. Однако, учитывая трудоёмкость этого метода, была разработана математическая модель для нужд решения задач, сформулированных на основе общего гидравлического анализа. Математическая модель была сформулирована при предположении, что в гидравлически длинных водоводах, целиком заполненных сточными водами, выступает напорное течение, вынужденное насосами.