Contributions to simulation of the non-permanent movement in sewerage collectors

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Abstract: The water movement of the sewer collectors is of a non-permanent type because of the variation in flow over time. Non-permanent movement in collectors is mathematically modelled by the Saint Venant equations. To solve the equation system, the characteristic method was used, provided that both equations are quasi-linear in the unknown \( h \) and \( Q \). Non-dynamic contouring conditions are given by the hydraulic feature of the collectors / tanks located on the collector. Dynamic contour conditions are rendered by the collector-specific equations (river level effluent hydrograph, manoeuvring parameters of the boiler, manoeuvring characteristics at pumping stations, etc.). For the mathematical model implementation, a computational program was developed in the Matlab programming environment (Variation Gradual Collector Program). The program was used to simulate the non-permanent movement in the main sewerage collector "Cacaina" from the sewerage network of the city of Iasi. The simulation of the non-permanent movement was done in two collector evacuation scenarios (gravity and pumping). The analysis of the results obtained for scenario 2 highlights the differential operation of the eight collector sections separated by the side feeders. Simulation of the movement has highlighted the exceeding of the minimum and maximum values of the parameters imposed by the operating rules.

1. Introduction
A sewerage network consists of a succession of collectors (closed section channels) on which hydro-urban public work structures are placed with the purpose of taking over and transporting waste water. The water movement in sewer networks in Romania is generally free flow (gravitational type) [1]. The main form of water movement in sewer collectors is non-stationary (non-permanent) but it can be considered as stationary (permanent) for longer time frames. This aspect is used in the sizing of sewer collectors [1], [2], [3], [4].

Most waste water sewage systems in Romania were designed and built for combined operation [1]. Various technical concepts, specific to Romania's economic and political development phases, were used during their design. The running of combined sewerage network systems has a series of problems determined by the rainwater regime. Climate change in the last time frame has aggravated the collectors’ operation during torrential rains. A particular problem is presented by the main sewer collectors, with visitable section, which take over the waste water (domestic + pluvial) and transport it to the discharge structure or the wastewater treatment plant.

The operational problems of the visitable sewage collectors that have occurred in the last time frame, especially sewage spills on the streets surface, have required research on the hydraulic regime and simulation of permanent and non-permanent movement in the longitudinal profile of the collectors [5]. The simulation of water movement in the collector requires precise knowledge of the initial and contour conditions existing in the longitudinal profile [6], [7], [9]. A large part of the main sewer collectors have sections which were modified from the original ones, and differ geometrically and hydraulically from the standardised sections. This situation requires special computational programs to design and verify
flow parameters. The purpose of this paper is to present the research conducted in order to make a computational program necessary to verify the non-permanent water movement in the main collectors.

2. The hydraulic – mathematical model

The water movement in a sewer collector is of non-permanent type. This type of movement is present especially in the takeover and transport of torrential rains. The drainage of the rainwater through the connection chambers located along the sewer collector amplifies the parameters of the non-permanent movement.

For the analysis and simulation of the non-permanent movement type in a visitable sewage collector, equipped with connection chambers, a hydraulic-mathematical model was developed, to which a numerical computational program was attached. The hydraulic model simulates the “waste water + pluvial water” movement in a collector in accordance to the boundary conditions and contour conditions required by the operational process [10].

Rapid and gradually varied non-permanent movements in sewer collectors can be analysed and/or simulated through complex mathematical models generally composed of: 1 - motion equations; 2 - the continuity equation; 3 - initial conditions; 4 - limit conditions [2], [3].

Non-permanent movement in collectors is mathematically modelled through the Saint - Venant equations, consisting of the mass conservation (the continuity equation) and the moment conservation equations. Saint - Venant equations can be mathematically rendered in both integral and differential forms, which are equivalent only if the dependent variables are differentiable [3], [8].

The differential forms of the equations were used in order to carry out the analysis model, respectively [2], [3],
- the continuity equation

\[ B \frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} - q = 0 , \]  

(1)

where \( Q \) is the flow; \( q \) - the specific inflow / outflow; \( B \) – the surface width of the bed; \( h \) – water depth; \( x \) – length; \( t \) – time;

- the convergent form of the moment conservation equation (the dynamic equation of the wave)

\[ \frac{\partial Q}{\partial t} + \frac{\partial }{\partial x} \left( \beta \frac{Q^2}{A} \right) + g A \left( \frac{\partial h}{\partial x} + S_f - S_o \right) = 0 , \]  

(2)

where \( S_o \) is the slope of the bed; \( S_f \) – the hydraulic slope; \( A \) – the area of the flow section; \( \beta \) Boussinesq coefficient. The \( S_f \) hydraulic slope, assuming that in the non-permanent movement the flow direction can be reversed, has the expression:

\[ S_f = \frac{|Q|Q}{K^2} , \]  

(3)

where \( K \) is the flow modulus.

From a mathematical point of view, (1) and (2) equations make a system of partial derivative equations, with \( t \), time and \( x \), spatial coordinate independent variables. The main dependent variables are \( h \), water depth and \( Q \), flow. A method of solving the Saint-Venant equation system, provided that both equations are quasi-linear for the \( h \) and \( Q \) unknown terms, is the characteristics method [2], [3].

The continuity equation (1) is quasi-linear; but to also prove the quasi-linearity of the dynamic wave equation (2), it was transcribed under the following form [3]:

\[ \left( gA - \frac{\beta}{A^2} Q^2 \cdot B \right) \frac{\partial h}{\partial x} + \frac{\partial Q}{\partial x} + \frac{2 \cdot \beta}{A^2} Q \cdot \frac{\partial Q}{\partial x} + gA(S_f - S_o) = 0 . \]  

(4)

In general, a system of two quasi-linear equations has the form [11]:

...
and is characterised by a matrix, defined as follows:

\[
A = \begin{pmatrix}
a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\
a_{21} & a_{22} & a_{23} & a_{24} & a_{25}
\end{pmatrix}.
\]  

(6)

The elements of the A matrix can be determined through the coefficients in (6.1) and (6.4) equations, as follows:

\[
\begin{align*}
a_{11} &= B, & a_{12} &= a_{13} &= 0, & a_{14} &= 1, & a_{15} &= -g, \\
a_{21} &= 0, & a_{22} &= gA - \beta q^2 B, & a_{23} &= 1, & a_{24} &= \frac{2\beta}{A}Qq, & a_{25} &= gA\left(S_f - S_0\right).
\end{align*}
\]  

(7)

It is found that, in general, \(A = A(t, x, H, Q)\), so the equations (1) and (4) first order equations as well as the equation (5) system are quasi-linear. For concrete analysis, the system of Saint-Venant partial derivatives equations must be solved considering a series of appropriate initial and limit conditions.

The assumption of permanent and non-permanent gradually varied movement is accepted at the \(t_i\) initial moment. The initial conditions follow the (9) Equation form and can be numerically rendered by the following triplets:

\[
(x_{0i}, h_{0i}, Q_{0i}), \quad \text{cu } i = 1, 2, \ldots, N_t.
\]  

(8)

The \(x_{0i}\) values for the \(x\) spatial coordinate are designed to include all significant variations for both the constructive and functional parameters of the collector. The (8) conditions can be expressed by the following three \(N_t\) - dimensional vectors:

\[
X_0 = \{x_{0i}\}, \quad H_0 = \{h_{0i}\}, \quad Q_0 = \{Q_{0i}\}.
\]  

(9)

There are two types of contour conditions: non-dynamic and dynamic. Non-dynamic contour conditions are based on the hydraulic characteristic of the hydro-urban public work structures present on the network. The dynamic contour conditions are given by specific equations, and the most common are: a - the hydrograph of levels in the effluent; b - the parameters for manoeuvring a weir valve; c - the pumping stations operational manoeuvring characteristics [10].

The limit conditions, defined in \(x = x_k, \quad (k = 1, 2, \ldots, N_{SC})\) sections, can be put into the following general form [11]:

\[
F_k(t, H_k^{am}(t), H_k^{av}(t), Q_k^{am}(t), Q_k^{av}(t), u_k(t)) = 0, \quad \text{for } t \in [t_0, t_f],
\]  

(10)

where:

\[
H_k^{am}(t) = H(t, x_k - \varepsilon), \quad H_k^{av}(t) = H(t, x_k + \varepsilon), \quad \text{for } t \in [t_0, t_f] \text{ and } \varepsilon \to 0,
\]  

(11)

\[
Q_k^{am}(t) = Q(t, x_k - \varepsilon), \quad Q_k^{av}(t) = Q(t, x_k + \varepsilon), \quad \text{for } t \in [t_0, t_f] \text{ and } \varepsilon \to 0,
\]  

(12)

and \(u_k(t)\) is the control vector from \(x = x_k\) section, having \(m_k \geq 0\) components (control units); \(F_k\) – operator of differentiated nature (system of algebraic or functional equations, tables, graphs etc.), having the following number of components [11]:

\[
m_k + n + 1, \quad \text{for } k \in \{1, N_{SC}\}; \quad m_k + n, \quad \text{for } k \in \{2, N_{SC} - 1\}.
\]  

(13)

When the variation laws of the \(m_k\) control units are predetermined, that is, the following functions are known:
\( u_k^v = f_{uk}^v (t), \quad (v = 1, \ldots, m_k), \quad \text{for} \quad t \in [t_0, t_f], \) \tag{14}

then this type of contour conditions are known as \textit{non-dynamic}, otherwise the contour conditions are \textit{dynamic}.

Due to the complexity of the mathematical model, flow problems in rapid varied non-permanent movements, gradually varied in the collectors of the sewage systems, can be solved only by numerical methods, of which the most used due to their efficiency are [2], [3], [7]: 1 - the characteristics method; 2 - the finite difference method. The characteristic method was used in the making of the hydraulic-mathematical model. Part of the elaboration details of the hydraulic - mathematical model are presented in the [5], [10] and [12] papers.

The algorithm designed was used to develop the TGCProg (Transient Gradually Varied Collector Program) computer program, necessary to numerically simulate non-permanent water movement in sewer collectors. The TGCProg computer program was validated through a representative test application in the field of prismatic beds free flow [10]. This computer program has the following features:

A. Solves verifying problems for complex sewer collectors in the Transient (Non-Permanent) Gradually Varied Movement.
B. The collector, considered an enclosed channel with sections with constant flow and slope, is made of standardised or non-standardised tubes with a complex cross-section consisting of line segments and / or circular arcs.
C. The main program enables the following operations:
   - entering input data directly from the keyboard and saving them to specialised data files;
   - entering input data from previously created and stored data files;
   - processing the output data and saving them into data files on the collector operating specialties;
   - appropriate graphical representations based on output data and in accordance to the requirements for the collector validation.
D. The main program calls, both directly and / or indirectly, the following six user functions for which the main features are specified [10]:
   1. \textbf{F1} - evaluates the coefficients of the base, processed and resulting equation systems, which define the transient water movement in the collector;
   2. \textbf{F2} - evaluates the value of a discontinuous function, with variations in stages;
   3. \textbf{F3} - generates a differences grid divided with a variable step along the x-x axis;
   4. \textbf{F4} - evaluates contour conditions at the upstream end of the hydraulic system (type II nodes);
   5. \textbf{F5} - evaluates contour conditions at the downstream end of the hydraulic system (type III nodes);
   6. \textbf{F6} - evaluates contour conditions in intermediate sections of the hydraulic system (type V nodes).

\textbf{TGCProg} computer program has the following working structure:

A. Menu with the codes used to define initial and contour conditions.
B. Input data:
   - B.1. Program constants
   - B.2. General variables of the problem
   - B.3. General variables on finite difference digitisation
   - B.4. Sizes and functions that define the equation system’s coefficients
   - B.5. General notations which appear in the contour conditions
   - B.6. General notations which appear in the initial conditions
C. Output data:
   - C.1. Values for independent and dependent variables
D. Specific notations for the computation scenario
   - D.1. Constants of the application
   - D.2. Specific data from system coefficient expressions
D.3. Specific notations from contour conditions expressions
D.4. Specific notations from initial conditions expressions

3. Results and discussion

The TGCProg computation program was applied to the analysis of non-permanent flow in a collector located in the sewerage network of Iaşi city in Romania (figure 1). The “C Main Sewer Collector”, referred in the paper as “C Collector”, is an enclosed channel with a length of 2.416 km. It transports the Cacaina stream waters, the waste water and the rainwater from the served area. The shape of the flow section is differentiated on the length of the collector (figure 2). The ST weir is placed at the upstream end of the collector, which allows controlled access of the water from the Cacaina stream. “C Collector” discharges downstream through the CD8 discharge chamber into the “D Main Sewer Collector”. On the “C Collector” route six chambers (CA1 - CA6) are located, in which lower order collectors with unilateral inflow discharge.

Figure 1. The structural network of “C Collector”: “C” and “D” – main sewer collectors; ST – weir; CA1 – CA6 and CD8 discharge chamber; SPE – evacuation pumping station; C II – C VIII sewer collectors.

The “C main sewer collector” is located on C.A. Rosetti Boulevard - first section and continues on Tudor Vladimirescu Boulevard - the second section (figure 3). The first section, with a limited length of about 300 m, has a circular shape (Dn 700 reinforced concrete tubes). The second section is located on C.A. Rosetti Boulevard and T. Vladimirescu Boulevard, with a length of 2.116 km and a mixed flow section (reinforced concrete box made of a semicircle and a rectangle with the dimensions of 3450/2250 mm) (figure 2).

The “C” sewer collector functions in an “unitary system”, which implies a non-permanent movement, especially in the case of torrential rains [14], [15]. The collector was rehabilitated on a series of sections, which changed the geometry of the flow section on a series of sectors [13]. The modified section no longer complies with the original (standardised) shape, due to the transition to a mixed type non-standard shape (curves + lines) [5], [10], [17], (figure 2).
Two operating scenarios were defined for the “C” Main Collector, with 1 - 2 analysis alternatives:

A - Gravitational discharging through the CD8 discharge chamber scenarios:
Scenario A1 - Bahlui River level is under the elevation of CD8 discharge chamber foundation.
B – “Tudor Vladimirescu” pumping station discharge scenarios:
Scenario B1 - The Bahlui River level is above the CD8 discharge chamber foundation;
Scenario B2 – Shut down of the pumping station caused by “power failure”.

The simulation of collector running in the non-permanent movement was accomplished in two work stages:

Stage I: Pre-processing of constructive and hydraulic data. The geometric and hydraulic data of the collector, considered as input data into the program, were processed in uniform and non-uniform permanent movement for the adopted analysis scenario (details in [5], [10], [17]). Data processing was done by categories, using specialised computing programs on each type of water movement [5], [10]. The processed data was entered into the files as “Input data” in the TGCProg computation program.

The technical data was stored in the $M$ matrix, $M = [h_C; BC; AC; RHC; zGC; WC; KC]$ in data file Hydraulic features Semicircle-rectangle.mat. The ST weir is located at the upstream end of “C” collector, which allows the controlled access of the water from the Cacaina stream. Downstream, the “C” collector discharges into the CD8 discharge chamber. The constructive and functional data of the “C” collector were centralised in the calculation tables (T1 – “C” collector parameters in longitudinal profile, T2 – Constructive parameters of unilateral supply chambers, T3 - Hydraulic - functional parameters of the collector). Figure 4 and figure 5 shows the water depth/share variation at initial moment ($t = 0$) on the “C Main Collector” ($h_N$ - normal depth, $h_{CR}$ - critical depth, $h_{GV}$ - non-uniform movement depth).
The analysis of the data in Figure 4 shows the variation of the water height at the initial moment in the collector at the length of 2116 m. Comparative analysis of normal depths and critical depths indicates the presence of a subcritical movement state ($h_N > h_{CR}$). The analysis of the water depth variation mode...
in Figure 5 shows a continuous non-uniform variation movement in the collector in the length of 2116 m. The varied gradual non-uniform movement is represented by a set of curves of the free surface of type a₁ (ascending) and b₁ (descending).

Stage II: Simulation of the computation scenario (scenario B2 is presented in the paper). Stage II has two main work phases:

II.1. Contouring conditions processing phase.
II.2. Basic data processing phase.

Since all six chambers on the “C Collector” path are coaxial, displaying the same values for the width and foundation elevation as it, the assumption of gradually and rapid varied non-permanent movement can be accepted in the collector. On some sections of the collector there may be a gradually varied permanent movement. Non-dynamic contour conditions are determined by the hydraulic characteristic of the hydro-urban public work structures present on the network (the six connection / discharge chambers, CA1-CA6). For the $Q_{af}(t)$ time variation of inflows in the CD1 - CD6 chambers, the following equation has been considered:

$$Q_{af}(t) = Q_{af}^0 \cdot Q_r(t),$$  

(15)

where $Q_r(t)$ is the relative inflow and has the same variation law for all six inflows.

Constructive, functional and general base data for any “C Collector” computational scenario are stored in the “Input Data” files. The files are FIS2_Collector and FIS3_Collector, respectively FIS4_Collector for the initial conditions. The files have been developed by computational programs for the permanent movement. Thus, all the base data can be entered into the TGCProg program by simply reading the three data files.

After running the program, the following output data resulted, which define the collector’s functioning in the operational scenario adopted:

1° - the value of the depth $h = h(t,x)$, for $0 \leq t \leq 4,496''$ and $0 \leq x \leq 2,115.75$ m.

To obtain a greater precision, the interval for $x$, $[0, 2115.75]$ m was subdivided by $N_{ph} = 100$ equidistant division points. For the time interval $t$, $[0, 4,496'']$, $N_{pk} = 1,200$ quasi-equidistant division points resulted. Thus, the solution $h = h(t,x)$ is represented by the following discrete values for $t$, $x$ and $h$:

$$(t_i, x_j, h_{i,j}), \text{ with } i = 1, 2, \ldots, N_{pk} = 100 \text{ and } j = 1, 2, \ldots, N_{ph} = 1200$$

(16)

The graphic representations were done with the values from equation (16). For tabular results, a lower number of equidistant division points was considered both along the $x$ axis, $N'_{ph} = 30$ ($\Delta x = 72.96$ m step), and the $t$ axis, $N'_{pk} = 30$ ($\Delta t = 150''$ step),

$$(t_i, x_j, h_{i,j}), \text{ with } i = 1, 2, \ldots, N'_{pk} = 30 \text{ and } j = 1, 2, \ldots, N'_{ph} = 30$$

(17)

For three representative values of the $x$ (m) spatial coordinate,

$$x \in \{687.00; 1108.25; 1649.00\}$$

(18)

the following explicit solutions have been selected from equations (16) and (17) solutions:

$$h_{0.7km} = h(t_j, 687), h_{1.1km} = h(t_j, 1108.25), h_{1.6km} = h(t_j, 1649)$$

with $j = 1, 2, \ldots$, Nph = 1200,

(19)

respectively,

$$h_{0.7km} = h(t_j, 687), h'_{1.1km} = h(t_j, 1108.25), h'_{1.6km} = h(t_j, 1649)$$

with $j = 1, 2, \ldots$, Nph = 30.

(20)
The equation (19) solutions are shown in the figure 6 graphs and the equation (20) solutions are centralised in table 1. The overall figure 6 curve rate corresponds from a quality point of view to the physical aspect of the phenomenon formed in the collector.

![Figure 6](image)

**Figure 6.** The maximum depth variation chart in three sections located on „C” Collector“:
- \( h_{0.7\ km} = 1.21 \) m, blue line;
- \( h_{1.1\ km} = 1.71 \) m, red line;
- \( h_{1.6\ km} = 1.64 \) m, green line.

2° - depth minimum values

\[
h_{\text{min}}(x) = \min_{0 \leq t \leq 4496^s} \{h(t,x)\}, \quad \text{for } 0 \leq x \leq 2115.75 \text{ m}
\]

for \( 0 \leq x \leq 2115.75 \) m.

3° - depth maximum values,

\[
h_{\text{max}}(x) = \max_{0 \leq t \leq 4496^s} \{h(t,x)\}, \quad \text{for } 0 \leq x \leq 2115.75 \text{ m}
\]

The variations of the minimum and maximum depths were presented tabular (table 1) and graphical on characteristic analysis lengths (figures 6 and 7).

**Table 1.** Maximum and minimum values for depths and levels in sections with contour conditions

| No. | Symbol | \( x \) (m) | \( h_{\text{min}} \) (m) | \( h_{G0} \) (m) | \( h_{\text{max}} \) (m) | \( Z_{\text{MIN}} \) (m) | \( Z_{\text{MAX}} \) (m) |
|-----|--------|-------------|----------------|----------------|----------------|----------------|----------------|
| 1   | Upstream | 0.00        | **0.94**       | 0.97            | 1.02            | 42.90          | 42.98          |
| 2   | 0.7 km   | 687.00      | 1.04           | 1.11            | 1.21            | 41.11          | 41.28          |
| 3   |         | 739.55      | 1.08           | 1.19            | 1.29            | 41.01          | 41.22          |
| 4   |         | 760.25      | 1.12           | 1.27            | 1.36            | 40.96          | 41.20          |
| 5   |         | 812.50      | 1.31           | 1.49            | 1.57            | 40.91          | 41.17          |
The extreme depths (marked with italic symbols in the table), which correspond to extreme filling degrees appear in the same sections as in the initial gradually varied movement: the maximum depth $h_{\text{max}} = 2.60$ m with $U_{\text{max}} = 1.00$ in the downstream section (complete filling of the section); the minimum depth $h_{\text{min}} = 0.94$ m, with $U_{\text{min}} = 0.36$ in the upstream section. According to the technical literature, the filling capacity of the main collector must be maximum 0.80 [14], [15].

![Figure 7. Maximum depths envelope curves ($h_{\text{max}}, h_{\text{GV0}}, h_{\text{min}}$) on „C” Collector”](image_url)

From the analysis of the obtained data, it is possible to analyse and interpret the forms of movement which appear in the longitudinal profile of the collector. The shutdown of the pumping station which discharges the torrential rain transported by the collector determines the exceeding of the admissible filling capacity, and also the pressurising of the flow section on the final sector (figure 7). The exceeding of the filling level indicates unsatisfactory functioning of the collector, as confirmed by field research.

The simulation conducted showed an important variation in the maximum depth values on some sections of the “C Collector”. The numerical results obtained with the simulation program were highlighted as follows: the maximum depth $h_{\text{max}}$ varies over a range of 1.02 - 260 m (progressive increase); the filling capacity of the collector varies from 0.36 to 1.00 (progressive increase) at the length of 2116 m; the maximum filling degree, $U_{\text{max}} = 1.00$, appears in the downstream section of the collector (so full section filling is achieved, situation which is unfavorable to the normal operation of the collector); the minimum depth varies over an interval of 0.94 - 1.87 m at the length of 2116 m.

Thus, on the final section it resulted the exceeding of the flow section height ($h_{\text{max}} = 2.60$ m), in which the filling degree became maximum ($U_{\text{max}} = 1.00$). It results that the movement of the free-flowing water is transformed into pressurised movement on that collector section.
By simulating the operation of the collector in the chosen scenario, elements can be taken into account to detect, in real time, the causes that cause the collector's faulty operation, and then, by eliminating or at least mitigating these causes, the collector safety can be increased.

4. Conclusions

The main form of water movement in the main sewer collectors is non-stationary (non-permanent), but over longer time frames it can be considered as stationary (permanent), which influences the hydraulic computation.

The TGCProg computer program solves problems consisting of verifying complex sewer collectors with flow sections in gradually in varied non-permanent movement, depending on various contour conditions existing in the longitudinal profile.

The TGCProg computer program is applicable to sewer collectors which transport waste waters + pluvial waters, and especially to the intake, transport and discharge of torrential rainwater.

The case study solved for a main sewer collector with a mixed section (rectangle + semicircle, with the dimensions of 3450/2250 mm), by using the TGCProg computer program, presents the water height maximum and minimum values, determined by the direct and the indirect wave, characteristic to the non-permanent movement.

The results of the research show the applicability of the TGCProg computer program in the study of non-permanent movements in sewer collectors, with the condition of knowing the initial geometric and hydraulic parameters in the cross section and the longitudinal profile for the permanent movement (TGCProg program works together with other 2 - 3 adjacent computation programs).

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