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A REVIEW ON METHODS OF SEWERAGE SYSTEMS OPTIMIZATION

The papers on the application of computer-aided computation techniques in solving the optimization problem of wastewater discharge system have been critically reviewed.

1. INTRODUCTION

First papers dealing with the optimization of wastewater removal were published in the sixties, i.e. about twenty years ago. The interest in this problem and the development of optimization methods have been strongly linked with a dynamic progress in computer-aided calculation technique. Since the design of sewerage system requires a great number of tedious mathematical calculations and a great number of variants or iterative cycles connected with its optimization, the earlier papers were of theoretical importance and did not find practical applications.

Many of the so far published in Poland [14], [15], [20], [23] and abroad [6], [10], [18], [19], [22] on the application of computers to design and analysis of sewerage systems have been concentrated on automation of calculations concerning hydraulic analysis of the system with the known technical parameters, and on design of longitudinal profile of sewers in which the difference in levels is the smallest possible. The profile selected in this way was not always the optimal one [2]. LIEBMAN [12] was the first to develop the optimization method for sewerage system using non-linear programming techniques. This method has no practical application since it is confined to one diameter of the sewer along all the segments of the system, it does not take a sufficient account of hydraulic laws governing the wastewater flow, and moreover, is confined to the sewerage system consisting of a few segments only.

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Employing the technique of linear programming, HOLLAND [8] solved the problems of the sewerage system optimization for different pipe diameters. The optimal diameters calculated according to his method do not correspond to the standard ones, thus the problem of choice of optimal standard diameters has remained unsolved. Algorithm of calculations was limited to small sewerage systems because of the work time and the required memory of the then produced computers were far from being perfect.

VOORHEES [21] worked out theoretical principles of the dynamic programming, paying a special attention to developing a correct model of the cost function for sewerages building depending on their diameters and sinking. Since neither algorithms nor computer program for this model were constructed, its applicability could not be verified.

ZEPP and LEARY [24] developed the optimization method based on the Verhees' model of cost function. In this method optimal parameters are determined in each segment of the sewerage system, starting with its beginning. This method does not lead to finding an optimal solution of the whole system, since optimal solution of partial problems do not give optimal solution of the whole problem.

The methods described did not satisfy the expectations, that is why they were not applied in engineering practice. They contributed, however, to development of the next, improved, optimization methods, which have been applied in design of sewerage systems. These methods, which will be described in the sequel, can be divided into four groups:

1) method in which a systematic search for solutions is applied,
2) method applying linear programming,
3) method employing the principle of dynamic programming,
4) method consisting in search for the optimum with the help of coupled gradients.

In the next part of the paper some methods included in the above four groups will be characterized in the chronology of their development.

2. METHOD OF A SYSTEMATIC SEARCH FOR SOLUTIONS

MIŁASZEWICZ–KICIŃSKA [16], [17] optimized a model collector led through settlers' areas of linear concentration, characterized by the lack of slope. In this model the collector constructed from cylindric pipes is equipped with intermediate pumps. It has been assumed that the optimization criterion is the minimum value of the synthetic index of economical efficiency of the sewage transport system (collector and intermediate pumps). The slopes of the collector bottoms and the related sizes of the pipe cross-sections, the number, spacing and delivery of intermediate pumps being the decision variables. For each segment of the collector the minimal and maximal admissible slopes of the bottom are calculated. Optimal solution is obtained by the method of systematic search for admissible solutions. The slope of the collector bottom is increased along its whole length, starting with the minimal one and increasing it each time by a percent of the difference between maximal and minimal values. The resulting slope of the collector ranges within the minimal and maximal one, at which the minimal value of the synthetic index of economic efficiency of the system is obtained. This has resulted in unproved conclusions on optimal slopes of various fragments of the collector, although the combination of different slopes on its all segments has not been analysed. The usability of the above method for design of collectors is also limited because of the additional assumptions that the area along the collector is flat and the sewage inflow is uniform along the whole length of the collector.

KULICZKOWSKI in [11] was concerned with the choice of an optimal solution of a given variant of the collector construction (reconstruction) in urban conditions. As the optimization criterion he assumed the minimal cost of the collector construction (reconstruction), which includes the cost of canal system construction (earth works, drainage of cuts, building of canals, and related works), additional costs due to the construction in urban area (road works, temporary and permanent export of the soil surplus relaying of the interfering systems, protection of the foundations of buildings, immediate sewage removal during reconstruction, etc) as well as cost of detours, caused by closing some streets during the works (loss of time connected with detours, increased cost of fuel, and increased number of accidents). Optimization problem is in this method composed of two partial problems, which may be solved either independently or jointly. First partial problem refers to the choice of the optimal profile of the collector route. This route and its data are established at its beginning and end. In the nodes the canals are connected with their bottoms. Such objects like intermediate pumps, storage reservoirs, etc, are not taken into account. Exploitation cost, being insignificant in the case of collectors, is neglected. Limitations concern diameters of canals, sinkings and sewage flow rates. Obstructions and objects along the collector routes (also the designed ones) are taken into considerations. The problem is solved by means of systematic searches of solutions. To this end the collector is divided into segments characterized by the same input data (sewage flow rate intensity, slope of the ground, ground and water conditions, method of construction, organization of detours, etc). On each segment of the collector, the slope is changed step-wise by a certain value, starting with the minimal one. In this way one obtains all the combinations of the possible and admissible slopes of bottom on each segment of the collector, these combinations being related to all the combinations obtained for the previous segment. The numerical application of this method is limited due to long computer working time and to a large area of the memory occupied. That is why the author proposed two more efficient methods. One is the Monte Carlo method, the basic tool of which is the generator of random numbers. The numbers sampled are used to look for the values of the canal bottom decline on each its segment. The coupled gradients method of Rosenbruck is the other method suggested by Kuliczkowski and it is used to search for the minimum of function over a multidimensional space. The two methods use standard library programs. Results of calculations performed by these methods are not known. The second partial problem is concerned with the choice of an optimal rate of works on the separate segments of the collector and the choice of the optimal method of its construction. Solution of this problem is based on the results obtained from the first partial problem. At first one establishes the optimal rate of works on each segment and then the maximum possible number of alterations of this rate.

Finally, using the method of systematic search for all the combinations of segments in which the rates of works are different (from one to the maximal possible number of alterations), the optimal solution is found which, in turn, may be taken into account in the first partial problem. The author describes the method of selecting an optimal variant of the collector construction (reconstruction), among the variants with different assumptions, e.g. different routes of the collector, different sewerage systems, different objects on the road of the collector, etc. The Kuliczkowski's method has been applied to analysis of the reconstruction of sewerage collectors in the city of Wrocław. Time-consuming calculations, large operating storage occupied by the computer and the fact that not all the possible solutions can be considered because of the step-wise search for the optimum, are the main disadvantages of this method. As far as the practical application of this method is concerned the main difficulty consists in preparation of data concerning the cost of detours and construction in urban conditions. This is because of many factors by which these costs may be influenced. In this method the hydraulics of the wastewater flow in collector is not considered either. Despite these shortcomings this method is the first one in which the effect of urban conditions on the realization cost is taken into account.

3. METHODS IN WHICH LINEAR PROGRAMMING IS APPLIED

Dajani, Gemmell and Morlok [4] considered the advisability and possibility of the optimization of municipal sewage removal system, based on a deep analysis of external factors influencing the optimal design of the system. They stated that the cost of sewerage system construction, of which 85% is spent for pipes and 15% for gully and connecting sinks, was the main part of the total cost of the system. As the optimal routes of canals they proposed the shortest connections of the system nodes, and in doubtful cases the routes determined from the analysis of a limited number of variants, by means of available programs for a conventional design of sewerage system. Since the choice of the optimal route was not the subject of optimization, these routes have been assumed as being given. The authors have shown that in the United States the cost of canal construction is well approximated by a square function of the diameter and depth of escavation. This relationship was transformed by then into form in which the cost of construction is the function of the canal decline, assumed as a decision variable. The hydraulic model was based on the Manning's formula. Maximum daily sewage flow intensity was presented in the form of its dependence on the average daily intensity. The limitations assumed concern the canal diameters, rate of sewage flow and canal sinks. They are transformed into the conditions limiting the decision variable (decline). Optimization problem was solved by a segmentary linearization of nonlinear components occurring in the goal function and under limiting conditions, and then by the adaptation of the available algorithms of linear programming technique. Optimization by this method yielded the solution in form of a non-standard series of the canal diameters. The authors did not give the method for the solution of optimization problem in the case when the diameters were limited to commercial series and type of pipes. Thus the solution obtained by this method should be treated as an approximate one, from which, after the choice of the possibly corresponding standard diameters, a real solution approaching the optimal one may be obtained. The difficulty in the application of this method is due to sudden non-proportional increase of the occupancy of computer operating storage and computing time occurring with the increasing size of the system.

Dajani and Hasit [5] improved the method described above, considering a model of gravitational sewerage system with the fixed routes of canals made from circular pipes. Minimal cost of the system construction is the optimization criterion. The cost includes solely the pipes. Like previously, cost of construction was approximated by assuming that it is a square function of diameter and depth of cut. This dependence was further transformed so that the cost of construction be the function of only one decision variable — the decline of the canal bottom. Hydraulic relations are again described by the Manning's formula. The limitations concern the diameters, sinks of canal and sewage flow rates. In order to obtain a numerical solution, non-linear components of the goal function were linearized by segments. The problem formulated in this way was solved by the method of linear programming. The solution gives non-standard diameters totally filled. In order to obtain the solution with typical diameters filled totally, some additional constraints have been introduced. These are two equations for each segment of the system at a time, in which the variables are given by integers (zero and one). In this way the linear programming is extended, including programming with integers. The combination of diameters and declines must be given by the designer, from the solution obtained for non-typical diameters. The number of combinations is related to the number of integer variables, thus it is also connected with the matrix size of the problem. The combinations that do not satisfy limiting conditions should be eliminated. Integer programming yields the solution with standard diameters for entirely filled canal cross-section. This solution does not include intermediate variants for partially filled canal. Introducing such a possibility, for each variant of the canal diameter one considers different variants of declines which must, however, guarantee the self-purification velocity in the canal. In the above problem formulation the limitations of diameters and velocities, as well as linearization of one of the nonlinear components of the goal function are eliminated. In order to restrict the number of combinations the following procedure was suggested: to solve the problem assuming that the changes of diameters are continuous, then to analyse the declines of the canal bottoms (and the related diameter) differing by 50 % from the solution obtained. In the example of calculation it has been shown that the minimal value of goal function for: a) full number of combinations of diameters and declines, b) a number of combinations with restriction of declines (and diameters) to $\pm 100\,\%$ of decline and c) a number of combinations with restriction of declines (and diameters) to $\pm 50\,\%$ of the decline (obtained in b) and c) cases at the assumption of continuous changes of diameters) is the same. It means that the solution obtained at the assumption of a continuous change of diameters is a good starting point for the solution of a problem with standard partially filled diameters. From the calculations performed it follows that the cheapest solution is obtained when continuous changes of diameters are assumed; in this case the computation time is also the shortest one, but the solution has no practical applicability. Solution of optimization problem at a discrete change of diameters and for fully filled canals gives a worse result and is more time consuming, but it may be applied in practice. Finally, for standard diameters partially filled, an intermediate (lying between the former solutions) cost of building is obtained; the solution may be applied in practice, but the computation time was the longest one. Hence, it has been concluded that the latter solution method should be improved by reducing the computation time. In the method described some objections concern the number of combinations of diameters and declines, when standard diameters and partially filled canals are assumed. At the given diameters and partially filled canal the decline of the canal bottom is a decision function influencing the value of the goal function. Since the value of goal function increases with the decline, the latter should be the least possible, i.e. precisely such a one, at which the self-purification velocity is achieved. Thus, there is no need to consider other than this one variants of decline for one standard diameters. This method, requiring long time of computations and high occupancy of operating storage because of a great number of variants to be analysed, is suitable for not large sewerage systems.

4. METHODS EMPLOYING THE PRINCIPLE OF DYNAMIC PROGRAMMING

Czeczik, Odelska and Cal [3] analysed an optimal solution for a model system of a branched gravity sewerage system consisting of pipes, inspection chambers, connection wells and decline chambers. Minimal cost of the system construction is the optimization criterion of the system's operation, while the declines of bottom and the related diameters of the canal segments are the decision variables. Solution of the problem must satisfy the constraints (limiting conditions) imposed on canal diameters, sewage flow rate, depth on which the canal is laid, including underground obstacles and decline in decline chambers. The sewage flow rate in the consecutive segments of the system should increase toward the outlet. Local hydraulic losses in sink basins are taken into account. The solution of the problem is based on the principle of dynamic programming. In optimization procedure the segment between two successive inspection chambers is the least element of the system considered in computations.

The procedure is begun by determining in each inspection chamber the points laying on different depths. These points are obtained by division of the admissible range of the depth of canal bottom into several equal parts. Then, all the admissible combinations of connections (trajectories) of these points in two neighbouring inspection chambers are made, starting with the initial segments of the system. Thus in each point of an arbitrary inspection chamber (except for the first one) several trajectories comprising the segments before the chamber may be terminated and several trajectories containing the segment after this chamber may be initiated. All the trajectories occurring in an arbitrary segment are considered to be conditionally optimal, and for each of them all the trajectories of the former segment being its extension are analysed. It has been assumed that in inspection chambers the canals are connected with their bottoms. Thereupon those trajectories that do not satisfy limiting conditions are rejected and from the remaining trajectories those are selected which give the least cost of canal construction (from the beginning of the system to the segment considered).

As a result of the above procedure performed on all the segments of the system, an optimal trajectory, i.e. that for which the construction cost is the least, is selected on the last segment (at the outlet) out of the conditional optimal trajectories. Such a trajectory defines univocally the variant optimal for the whole system. In the case of connection wells all the possible combinations of trajectories of the canal segments meeting in the inspection chamber (including chambers if there are differences betweeen the bottoms of canals meeting in the chamber) are taken into considerations. Similar procedure is employed in the case of underground obstacles or sudden change in the slope of ground, i.e. decline chambers are considered in the admissible variants. In this method the objections concern the division of system into the segments between inspection chambers, despite the fact that external input values on computation segments (consisting, in general, of several segments between the chambers) are constant. This division results in the increasing number of the variants considered. This number depends mainly on the number of head points in each inspection chamber. Increase in the accuracy of the computations is connected with the increasing number of these points, thus also with a rapid increase of the number of variants that must be analysed. No reasonable principle, according to which the number of these points is to be established, was given. Some objections concern also the principle that the rate of sewage flow toward the outlet increases. This method in the case of optimization of large system requires long computation time and large operating storage.

MERRIT and BOGAN [13] developed a computer programme enabling the optimization of the gravitation, branched sewerage systems of the same type of transversal canal sections. In this programme the principle of dynamic programming was applied. It slightly differs from the method described before. In hydraulic model minimal flow rate at minimal flow intensity and maximal flow rate at maximal flow intensity are considered. The canal segments are connected in nodes by equalizing sewage levels. After the maximal admissible caving of the canal bottom, the solution with an intermediate pumping station is admissible. In the case of a great number of variants obtained, zone of admissible canal cavities (restricted by minimal and maximal admissible cavity) may be divided into several ranges. The analysis of the effect of fordesigns on optimization results is of much interest. It has been shown that: reduction of infiltration water amounts (insulating of the canal), increase of maximal admissible rate of sewage flow (special linings of the canal bottom), reduction of the declines of initial segments of the system (more frequent washing of those segments), reduction of the minimal admissible cavity of canals, and reduction of the value of the coefficient n in Manning's formula (more smooth pipes) exert a significant effect on the reduction of cost of the sewerage system to subject optimization.

ARGAMAN, SHAMIR and SPIVAK [1] have elaborated a method of an optimal choice of profiles and routes of gravitation branched sewerage system with a layout of canal network. Here the optimization criterion is minimal cost of the system construction, comprising building cost of canals, inspection and decline chambers, and connection wells. Hydraulic models employ the formulae of Manning and Pomeroye. The computations are based on the average daily sewage flow intensity, counted, in turn, for minimal and maximal flow intensities to determine finally the corresponding minimal and maximal rates of sewage flow in canal. Hydraulic losses in nodes are neglected. Restrictions concern diameters and cavities of canal bottoms and sewage flow rates. Final cavities of the system are imposed by the designer. The flow directions are established on each segment of the sewerage system. Decline chambers may appear only in nodes. For the system analysed the so-called run-off lines are made. These lines (not existing in reality) connect all the nodes distant from the system outlet by an equal number of segments. The problem is solved in stages by using dynamic programming method. One stage comprises minimization of construction cost of the system elements. Diameters and declines of each segment as well as directions of sewage run-off from each node (if there are several possible directions) are decision variables. It means that the tree of graphs (i.e. the routes of collectors and collector manifolds) is constructed in the course of optimization. To this end to each node there is introduced an integer variable — vector, the length of which is determined by the number of possible connections of the given node with the nodes of the neighbouring run-off line closer to the outlet. This vector assumes the value 1 in the case of main canal or collector pipe manifold, and the value 0 in case of a lateral canal. The procedure begins with the run-off line most distant to the outlet. In each optimization stage all the possible variants of the connections of nodes lying on two neighbouring run-off lines are considered. In each variant of the connection of two nodes various possibilities of the choice of ordinates of the canal bottom in these nodes are taken into consideration. These ordinates result from the partition of the admissible range of the canal depths in a node into a certain number of intervals. Thus, in each optimization stage the best variants of the route and profile of those system's parts, which take off the sewage to the nodes lying on one (closer to the outlet) run-off line, are chosen for each depths of all these nodes. The remaining variants are rejected. This procedure is terminated on the run-off line passing through the well nearest with respect to the outlet. Then the cheapest (but satisfying technological demands) variant ending on this run-off line is chosen. This variant is univocally determined as the optimal one of the whole system. Computation time and the required size of the computer memory depend on the number of nodes on each run-off line, number of possible directions of sewage outflows from each node, and on the number of possible ordinates of the canal bottom in each node. Because of a great number of the possible variants of the system the optimization analysis of all these variants is not possible. Therefore, in order to reduce the number of variants subject to analysis, each of nodes lying on the same run-off line (more distant to the outlet) is treated as being independent of others, i.e. the canals issued from it are optimized independently of the canals issued from other nodes. Due to such a simplification optimal solution may be also approaching the optimal one. Despite this fact, the simplification made by the method described may be applied only to small sewerage systems, because computation time and the required operating storage increasing rapidly with the increasing area of the system. Both the parameters increase much faster than in the method described before, which is connected with additional combinations of the possible routes of sewage transportation. Larger sewerage systems may be divided into fragments and optimize each fragment separately. There is, however, no certainty that the sum of the determined fragmentary optimal solution is equivalent to the optimal solution of the whole problem. In this method, like in the former ones, the head points must be determined in each chamber.

All the so far described methods, in which the principle of dynamic programming is employed, choose the cheapest variant among the variants of the same cavity (depth) in the chamber and eliminate the remaining ones. This procedure may lead to the rejection of a more expensive variant the diameter of which is smaller than in the cheapest variant, but which could appear to be the optimal one, because of the condition that the diameter in consecutive segments of the canal in the direction of its outlet must not be reduced (this problem does not occur in the method [3], since such a constraint is not assumed there).

5. METHODS CONSISTING IN SEARCH FOR THE OPTIMUM WITH THE HELP OF COUPLED GRADIENTS

Gupta, Agarwal and Khanna [7] considered the optimization problem of multisegment gravitation sewerage system, with the established routes of canals. As the optimization criterion they assumed the minimal construction cost of the sewerage system consisting of pipes and typical inspection and chambers. The authors constructed for the purposes of their country (India) the goal function, being a non-linear, complicated dependence of the building cost of the system on the canal diameters and depth its laying. After a suitable transformation of this goal function they obtained the dependence of construction cost on only one decision variable, i.e. on the canal diameter. Hydraulic dependences in this model are discribed by Manning's formula. Hydraulic model includes the sewage flows at partially and fully filled canals. The computations are based on the peak flow defined as being 2.5 times higher than the average daily flow. The constraints are imposed also on diameters and cavities of canal as well as the wastewater flow rates. To solve the optimization problem formulated in the above way they used the computer programme based on the algorithm of the Powell's method of coupled gradients. The analysis of the solved optimization problems shows highly significant influence of initial segments of the system. These segments are in general not optimal, since their diameter results from the condition limiting the minimal canal diameter. Therefore these segments significantly affect the cavity, thereby the cost of farther segments of the system. In this method the computation time depends first of all on the choice of starting point, especially in case of large systems. The principle of the choice of this point has not been explained in the paper. Even with well estimated starting point the computation time and the computer memory occupied are high, which is connected with computation of the whole system repeated several times at least.

JONEJA, AGARWAL and KHANNA [9] solved optimization problem of a part of the sewerage system in Delhi canton (India). As the optimization criterion they assumed the minimal construction cost of the system of canals made from circular pipes, taking account solely of the material cost of pipes and earth works. Goal function is similar to that discussed in the former method; set of diameters of the system segments is the decision variable. Optimization calculations were performed for three fillings of the canals: 0.67 D, 0.81 D and 1.0 D, i.e. for which the sewage flow rate is identical as for canals filled entirely (0.67 D and 1.0 D) or the highest flow rate is achieved (0.81 D). Hydraulic relations are described by Manning's formula. Constraints are imposed on diameters and cavities of canals and sewage flow rates. To solve the problem three numerical methods of coupled gradients for finding the minimum function of many variables were applied. This means that the nonlinear problem with constraints was transformed into a sequence of problems without constraints consisting in search for the minimum on the given vectorial directions. Starting point was determined from the probable set of diameters. Optimization algorithms use the step determined by means of the least squares method. Convergence criteria are examined after each iteration step. The least troubles present the method, where the vector directions of search for minimum of the goal function are defined as being parallel to the axis of decision variables, i.e. when the minimum on such a direction is looked for, the value of only one decision variable is changed. The greatest saving in construction cost, if compared to the traditional design method, was achieved for the version with the full filling of canals. It has been stated that introduction of pumping station into consideration and introduction of hydraulic model in which the value of the coefficient n in the Manning's formula varies (depending on the canal filling considered), as well as further investigations on the improvement of the convergence of numerical methods are advisable. This method has the same shortcoming as those discussed earlier.

From the analysis of the examples calculated by the authors of the presented optimization methods, it follows that the cost of the realization of designs made according to the new — just described — methods is reduced within the range of 5–40 %, and that such result is much promising and further investigations should be undertaken. In the next publication we shall present the optimization method of the collector parameters in which the principle of dynamic programming will be applied in a new way.

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PRZEGLĄD METOD OPTYMALIZACJI SIECIOWYCH UKŁADÓW KANALIZACYJNYCH

Podano krytyczny przegląd literatury dotyczącej zastosowania komputerowych technik obliczeniowych do rozwiązywania problemu optymalizacji systemu usuwania ścieków.

EIN ÜBERBLICK ÜBER DIE METHODEN ZUR OPTIMIERUNG VON ROHRLEITUNGEN FÜR KANALISATIONSANLAGEN

Der Aufsatz enthält eine kritische Übersicht über Fachliteratur zum Thema: Anwendung von Computerverfahren zur Lösung von Optimierprobleme, die in Abwasserableitungssystemen auftreten.

ОБЗОР МЕТОДОВ ОПТИМИЗАЦИИ СЕТЕВЫХ КАНАЛИЗАЦИОННЫХ СИСТЕМ

Дан критический обзор литературы, касающейся применения компьютерных вычислительных техник для решения проблемы оптимизации системы удаления сточных вод.