Comprehensive optimization of the route, composition and parameters of transporting pipelines for various technological purposes

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Abstract. Pipeline transport is the most common in our country and abroad. All of Russia is entangled in a single system of oil and gas transport, which already permeate many European and Asian countries. At the same time, pipelines pass through swamps, pass through mountain ranges, cross seas and lakes. Group and district water pipelines cover thousands of populated areas, heat supply, water supply and sanitation systems cover cities and urban agglomerations. When designing such capital-intensive linear objects, one of the most important tasks is to trace them. The paper proposes to solve this problem in conjunction with the optimization of parameters of pipelines, pump and compressor substations, throttling devices and mating structures. The technique is based on a combination of discrete optimization methods and reflects the real processes of substantiating the structure and parameters of structures. The calculations of real pipeline systems showed high computational and economic efficiency of the proposed approach and its software implementation.

1. Introduction

Often, in the practice of designing, reconstructing, and developing pipeline systems for various technological purposes (transporting liquids, gases, multiphase media), the problem arises of optimizing the route and parameters of individual pressure and pressureless pipelines connecting two nodes, one of which is an intake node, the other is dumped. To solve this problem, a new approach is proposed, based on an algorithm for constructing shortest circuits and a dynamic programming methodology [1-10]. The essence of the proposed approach is to build conditionally optimal solutions between two given (initial - source and final - consumer) peaks in the graph of possible pipeline paths and its parameters (diameters and wall thicknesses of pipes, slopes, pressure boosting, pumping and compressor stations, differential and throttle structures). After reaching the final peak, from all conditionally optimal solutions, the best one is selected and the optimal pipeline route and the optimal parameters of pipelines and conveying structures are restored by reverse movement.

2. Methods

If we fix the topology of the pipeline network, then the problem arises of choosing the optimal number of discrete values: the diameters of the pipelines, the pressure of the pumping stations and throttle
devices. Essentially, the problem arises of finding the optimal piezometric surface of a moving medium (water, gas, oil product).

The search for such an optimal piezometric can be represented as a multi-step control process, characterized by the following values.

The control variables are the pressure losses \( h_i \), the pressure of the pumping stations \( H_i \) (-), throttle devices \( H i (+) \):

The phase variables are nodal piezometric heads (free surface marks) at the beginning and at the end of the calculation section \( i \) (there will be \( Z \) and \( C \), respectively):

\[
P_i(n) = \{P_{z(n)}\}; \quad \text{where } z \in Z_i,
\]

\[
P_i(k) = \{P_{c(k)}\}; \quad \text{where } c \in C_i.
\]

The sequence of which \( P(n) = \{P_{1(-)}, ..., P_{n(-)}\}, P(k) = \{P_{1(k)}, ..., P_{n(k)}\} \) is the set of possible states of the systems under consideration.

It should be noted that for section \( i \), the initial variables are associated with the following final relations:

\[
\begin{align*}
\text{P}_{c(k)} & = \text{P}_{z(n)} + h_y - H_i; \\
\text{P}_{c(k)} & = \text{P}_{z(n)} + h_y + H_v. 
\end{align*}
\]

In formulas (1), \( h_y \) represents the pressure loss values over the network sections, which for different transported media they have different hydraulic ratios.

Due to the discreteness of the control variables, the transition from \( P_{z(n)} \) to \( P_{c(k)} \) cannot always be carried out, i.e. there is not always such a combination \( h_y, H_i, H_v \), so that condition (1) is satisfied. In this case, it is advisable to take as phase variables not their point values, but some subsets:

\[
\begin{align*}
P_{i(n)} & = \bigcup_{c=1}^{c=1} P_{c(n)} \quad \text{so that } \bigcap_{c=1}^{c=1} P_{c(n)} = 0 \\
P_{i(k)} & = \bigcup_{z=1}^{z=1} P_{z(k)} \quad \text{so that } \bigcap_{z=1}^{z=1} P_{z(k)} = 0.
\end{align*}
\]

Algorithmically, this is done by dividing \( P_{i(n)} \leq P_{c(n)} \leq P_{i(k)} \leq P_{c(k)} \) into \( z \) and from intervals. If \( P_{z(n)} P_{z*} (n) \), then it is considered that a transition has been made from the initial (input) to the final (output) phase variables.

Under the condition of discrete values of the controlled variables \( h_i, H(-), H(y (+)) \), the objective function in the form of life cycle costs [11,12] has the following form:

\[
F(P, h, H) = \sum_{i=1}^{n} F_i \left( h_i, H_{i(+)}^{(1)}, P_{i(-)}^{(1)}, P_{i(k)}^{(1)} \right)
\]

and is represented as an additive function of many variables.

We consider in more detail one step \( i \) of the control process, first in \( h_i \) and then in \( H_i \).

It is necessary to choose a control \( h_i \), that would translate the initial state \( P_{z(n)} \) to the final \( P_{c(k)} \) and minimize the objective function \( \Psi_i \left( P_{c(k)} \right) \), which consists of the costs obtained in the previous optimization step and the costs associated with transition from \( P_{z(n)} \) to \( P_{c(k)} \) according to (1):

\[
\psi_i \left( P_{c(k)} \right) = \psi_i \left( P_{z(n)} \right) + F_i \left( h_i, P_{c(1)}, P_{c(1)} \right).
\]

Since there are \( z_i \) initial states, the optimal transition to any final \( P_{c(k)} \) from all possible initial states \( P_{z(n)}, z = 1, ..., z_i \) by analyzing all admissible controls \( h_y, y = 1, ..., Y_i \) will be called conditionally optimal solutions.

In view of the foregoing, the functional equation for calculating conditionally optimal solutions for \( h_y \) at step \( i \) is written as follows:
According to this expression, the conditionally optimal solution corresponding to the phase variable \( Z \) at the beginning of the section is obtained by minimizing (or finding the best) transition to \( P_c \) from any admissible states \( P_z (n) \) (\( z \) runs through the values \( z = 1, ..., z_i \)) using controls \( h_y \) (\( y \) runs through \( y = 1, ..., Y_i \)). Moreover, for each analyzed \( P_z (n) \) and \( h_y \) the numerical value of the cost function \( F(h_y, P_c, P_z) \) is determined according to (2) in the pipeline construction. Only those controls for which condition (2) holds are taken into account:

\[
P^*(c) = P^*(n) + h_y, \quad z = 1, ..., z_i, \quad y = 1, ..., Y_i.
\]

It is determined in which of the intervals of the initial phase variables each of the obtained \( P_y (s) \) falls.

The best decision to remember:

\[
\Psi_i \left( P_c \right) = \min \left\{ \Psi_i \left( P_c^{(s)} \right), \Psi_i \left( P_c^{(c)} \right) \right\}
\]

As a result, functional equations can be written separately for pump and throttle structures:

\[
\Psi_i^{(HC)} \left( P_c \right) = \min_{h_u, u \in U} \left\{ \Psi_i \left( P_c^{(y)} \right) + f_i^{(HC)} \left( H_u \right) \right\};
\]

\[
\Psi_i^{(a)} \left( P_c \right) = \min_{h_v, \mu \in V} \left\{ \Psi_i \left( P_c^{(y)} \right) + f_i^{(a)} \left( H_v \right) \right\};
\]

The best decisions are remembered:

\[
\Psi_i \left( P_c \right) = \min \left\{ \Psi_i \left( P_c^{(s)} \right), \Psi_i^{(a)} \left( P_c \right), \Psi_i^{(c)} \left( P_c \right) \right\}
\]

In view of (5), (6), the optimal transition from any \( P_z (n) \) to the initial state \( P_c (k) \) by controlling with respect to \( h_u, N_i, H_v \) is carried out:

\[
\Psi_i \left( P_c \right) = \min \left\{ \Psi_i \left( P_c^{(s)} \right), \Psi_i^{(HC)} \left( P_c \right), \Psi_i^{(a)} \left( P_c \right) \right\}
\]

As a result of a multi-step process of minimizing the cost function, the following parameters are determined: the diameters of new pipelines and the thickness of their walls; areas where the construction or modernization of pumping stations and throttle devices is necessary.

If, for example, a sewer collector is designed that has one node for the flow of wastewater and one discharge node, then the multi-step optimization process can be organized either from the subscriber node, since the ranges of phase variables are usually determined for it, or from the discharge and sink unit on CBS, for which the values of \( \Pi (k) \) are fixed. Figure 1 shows the process of building up conditionally optimal solutions according to (4), (5), (6) and the optimal territory is shown in pink. Figure 2 shows the optimal profile obtained as a result of the computational process according to the specified formulas.

Based on the foregoing methodology for optimizing the parameters of the pipeline and pipeline structures, we propose a methodology for the comprehensive optimization of the route and parameters of the pipeline.

At the same time, the concept of a redundant design scheme is introduced - a graph of possible options for passing pipeline routes and possible locations for pipeline structures. Formed by the designer.

The first step of the method is to break down all nodes of the redundant graph into two subsets: \( J_g (v) \) - nodes that form the subtree and \( J_x (v) \) - nodes of the subgraph outside the tree, \( v = 1, ..., N \). Next, an iterative calculation process is organized, consisting of six stages.
1. In the array Jx (v) the numbers of all nodes of the circuit are entered, and in Jg (v), initially filled with zeros, only the node j corresponding to the source is entered. For all nodes, two arrays of phase variables are formed. The first of them contains C pairs of elements Pjc and Ψjc (Pjc), and the second consists of z groups of elements, each of them includes the node number j, from which the transition to the node j + 1 takes place; the number of the corresponding interval z, with which we arrive in the interval with; hy control number and Ni and Hv control number. For the subset j ∈ Jg (v), the values Ψjc = 0, and for j ∈ Jx (v), Ψjc = ∞. At this stage, v = 0.

2. In the subset Jx (v), nodes j + 1 are defined that have connections with the node j ∈ Jg (v), and conditionally optimal solutions are built up for the branches corresponding to them.

3. For each interval C, the conditionally optimal solutions obtained in stage 2 are compared with the existing solution at j + 1 ∈ Jx (v):

\[
Ψjc = \min \{Ψj(Pc(H)), Ψjc\}
\]

The best of them are remembered, and the corresponding values are recorded in the information arrays. Then, for each node, the maximum gain is determined:

\[
Ψjc = \min_{C} \{Ψjc, j \in Jx(v)\}
\]

Figure 1. Building conditionally optimal solutions

Figure 2. Optimal collector profile
4. Among the optimums for subgraph nodes outside the tree, the best one is selected:

$$\Psi = \min_{j \in J(V)} \left\{ \Psi_j \right\}$$

and the corresponding node goes into the subset $J_q (v)$.

5. We take $v = v + 1$ and calculations 2-4 are repeated until $v$ becomes equal to $m - 1$, which will correspond to the transition of all nodes from the subset $J_x$ to $J_g$.

6. For the drain node, among the conditionally optimal solutions, the best one is selected and, by returning through the information arrays, the optimal values of the system parameters and the path leading from the source node to the drain node are restored.

As an illustration of the operation of the described algorithm, we consider the redundant network (Figure 3, a) with the dimension: $m = 9; n = 12$. The source in it is node 1, and the sink is 9. Then $j \in J_x (0)$ will correspond to node 1, $\Psi_1 = 0, \Psi_j = \infty, j = 2, ..., 9$. Nodes 2 and 4 are adjacent to 1, and therefore, for conditional plots 1-2 and 1-4, conditionally optimal solutions are built up (Figure 3, b). For the final phase variables of the analyzed sections, the maximum payoffs $\Psi_4$ and $\Psi_2$ are determined, which, in turn, are compared with each other: $\Psi = \min \{\Psi_4, \Psi_2\}$ and node 4 goes to the subset $J_g (1)$.

The next step is to identify the nodes adjacent to the 4th node. They will be 7 and 5. Further, conditionally optimal solutions are already being built up for sections 4-7 and 4-5, maximum wins are determined and a comparison is made:

$$\Psi = \min \{\Psi_2, \Psi_5, \Psi_7\} = \Psi_2.$$

Node 2 goes into the subset $J_g (2)$ (Figure 3, c). For node 2, 5 and 3 will be adjacent, therefore, the building up of conditionally optimal solutions is carried out in sections 2-3 and 2-5. Since for node 5, $\Psi_5c$ is different from $\infty$, then for each phase variable $c: c = 1, ..., c$, the conditionally optimal solutions obtained by branches 4-5 and 2-5 are compared. The best values and the corresponding paths from 4 or 2 to the source are stored in information arrays. Then, according to nodes 3, 5, 7, the maximum wins are determined, which are compared among themselves:

$$\Psi = \min \{\Psi_3, \Psi_5, \Psi_7\} = \Psi$$

a)  

b)
Figure 3 - Algorithm for optimizing the route and parameters of the main collector

Node 5 goes into a subset of Jg (3) (Figure 3, d), etc. Figure 3, k shows the optimal path obtained as a result of the return stroke, by restoring the optimal values of the parameters and the path leading from 1 to node 9.

3. Results and discussion
We show the effectiveness of this methodology on the example of justifying the route of a promising water supply scheme for the city of Irkutsk and the Irkutsk region from lake. Baikal. As an alternative option for laying the reservoir, a variant of its arrangement along the bottom of the Irkutsk reservoir
arose. The field of hydrological research, analysis of the formation of the banks and the movement of
the pumps identified five possible routes for the passage of the collector with a deepening in the bottom
of the reservoir. Based on these options, a redundant water supply scheme has been compiled, presented
in Figure 4.

![Figure 4. Excessive scheme for optimizing the pipeline along the bottom of the Irkutsk reservoir](image)

The length of the reservoir along the fairway is 57 km. to deepen the pipeline into the bottom of the
reservoir to a depth of 1.5 m. For some sections, it is necessary to provide measures to prevent leaching
of soils, the formation of pumps, measures to protect against sludge, etc. As a result, the specific costs
of laying in different sections are different.

Taking into account the constructed redundant scheme and cost indicators for each possible section
of the collector route, calculations were carried out according to the method of complex optimization.
As a result, the optimal route option passed almost along the fairway of the Irkutsk reservoir and is
shown in Figure 5. Polyethylene pipes with a total length of 62 km and a pipeline diameter of 1.2 m.
The cost was 4.2 billion rubles. The residual pressure in the pipeline near the platinum of the
hydroelectric station was 0.28 MPa.
4. Conclusions

The developed methodology for the comprehensive optimization of the route and parameters of the pipeline intended for transporting liquids and gases was implemented in the Trace – VK software package [13], which is an effective tool for substantiating the structure and parameters of designed, reconstructed, and developing pipeline systems for various technological purposes.

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